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UNDERSTANDING THE DEPTH AND NATURE OF FLOW SYSTEMS IN THE
NASHOBA TERRANE, EASTERN MASSACHUSETTS, U.S.A.

A Thesis Presented

by

JOHN PATRICK DIGGINS, IV

Submitted to the Graduate School of the University of Massachusetts Amherst in partial
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Program in Geosciences

UNDERSTANDING THE DEPTH AND NATURE OF FLOW SYSTEMS IN THE
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by

John Patrick Diggins, IV

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Department of Geosciences

DEDICATION

To my parents for their tireless support and dedication.

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ABSTRACT

UNDERSTANDING THE DEPTH AND NATURE OF FLOW SYSTEMS IN THE NASHOBA TERRANE, EASTERN MASSACHUSETTS, U.S.A.

MAY 2009

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Directed by: Professor David F. Boutt

Igneous and metamorphic rock units have long been considered marginal aquifers yet they are a significant source for potable drinking water in many areas worldwide. Additionally, use of these systems is on the rise due to many factors including, contamination and overuse of surficial systems, as well as expanding population and drought. The Nashoba terrane is a fault-bounded block of high-grade, steeply dipping metavolcanic and metasedimentary rock located in eastern Massachusetts, U.S.A. The Nashoba is northeast trending, extending from Oxford, MA to the Gulf of Maine south of Newburyport, MA. Seventeen previously drilled wells throughout the Nashoba were selected for use in this study. The goal of this study was to characterize the hydrogeologic system of the Nashoba Terrane.

Wells studied were in three bedrock types: granite, schist and amphibolite. Three fracture types were identified: FPF, subhorizontal unloading joints and tectonic joints. Several major fracture orientation sets were also identified including northeast trending FPF, east-west trending and north-south trending tectonic joints as well as northwest trending tectonic joints. Dominant sets varied in the three rock types and the frequency of fractures was found to decrease with depth.

Only four percent of all fractures measured in this study were flowing. Approximately 32% of the flowing fractures were northeast trending, 17% of subhorizontal fractures were flowing and the remaining 51% were of variable orientation and dip. In general, the orientation of fractures was not found to determine whether a fracture flows, nor was rock type a significant determinant of flow. There was no flow identified below 170 meters and the majority of flow in the Nashoba Terrane is constrained to the upper 100 meters. This is most likely due to decreased fracture frequency and permeability with depth. This study is significant to the search for a sustainable groundwater source in bedrock because results show that the few fractures are actually contributing to flow and that flow is primarily occurring near the surface.

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PROLOGUE

The contents of the thesis are the results of a borehole geophysical study of the Nashoba terrane undertaken during the summer and fall of 2007. The purpose of this thesis is to describe the discrete fracture flow systems of the Nashoba from the view of the seventeen bedrock wells studied. This thesis is broken into two chapters which are described below.

Chapter one, titled *Fracture flow characterization of selected wells in the Nashoba terrane using borehole geophysical techniques*, is a complete synopsis of all of the fracture and flow data collected in this study. Contained within Chapter One is a full description of every well studied, including location, geologic setting and all fracture and flow data collected in each well. Finally, Chapter One contains an analysis of all summary fracture data.

Chapter Two, titled *Understanding the depth and nature of discrete fracture flow in the Nashoba terrane, eastern Massachusetts*, is a brief analysis of the relationship between fracture frequency, permeability and depth. Chapter Two is styled for publish in a geology journal.

CHAPTER 1

FRACTURE FLOW CHARACTERIZATION OF SELECTED WELLS IN THE NASHOBA TERRANE USING BOREHOLE GEOPHYSICAL TECHNIQUES

1.1 Abstract

Igneous and metamorphic rock units have long been considered marginal aquifers yet they are a significant source for potable drinking water in many areas worldwide. Additionally, use of these systems is on the rise due to many factors including, contamination and overuse of surficial systems, as well as expanding population and drought. The Nashoba Terrane is a fault-bounded block of high-grade, steeply dipping metavolcanic and metasedimentary rock located in eastern Massachusetts, U.S.A. The Nashoba is northeast trending, extending from Oxford, MA to the Gulf of Maine south of Newburyport, MA. Seventeen previously drilled wells throughout the Nashoba were selected for use in this study. The goal of this study was to characterize the hydrogeologic system of the Nashoba Terrane.

Wells studied were in three bedrock types: granite, schist and amphibolite. Three fracture types were identified: FPF, subhorizontal unloading joints and tectonic joints. Several major fracture orientation sets were also identified including northeast trending FPF, east-west trending and north-south trending tectonic joints as well as northwest trending tectonic joints. Dominant sets varied in the three rock types and the frequency of fractures was found to decrease with depth.

Only four percent of all fractures measured in this study were flowing. Approximately 32% of the flowing fractures were northeast trending, 17% of subhorizontal fractures were flowing and the remaining 51% were of variable orientation and dip. In general, the orientation of fractures was not found to determine whether a fracture flows, nor was rock type a significant determinant of flow. There was no flow identified below 170 meters and the majority of flow in the Nashoba Terrane is constrained to the upper 100 meters. This is most likely due to decreased fracture frequency and permeability with depth. This study is significant to the search for a sustainable groundwater source in bedrock because results show that the few fractures are actually contributing to flow and that flow is primarily occurring near the surface.

1.2 Introduction

Igneous and metamorphic rock units have long been considered marginal aquifers, yet they are a significant source for potable drinking water in many areas worldwide. Additionally, use of these systems is on the rise due to many factors including, contamination and overuse of surficial systems, as well as expanding population and drought. This is occurring in eastern Massachusetts, U.S.A., which is the focus of this study. Fractured crystalline rocks are characterized by low matrix permeability and strongly preferential flow paths, as well as extremely low porosity (<1%). Due to the virtually impermeable matrix, flow in these systems is primarily constrained to discrete features including fracture networks and large scale features such as faults. These factors make the rock and aquifer properties of these systems very different from classically studied aquifer materials (cemented and uncemented clastic sediments). In recent years, advances have been made in equipment, such as borehole geophysical and hydrogeological tools, as well as characterization techniques, which have advanced the conceptualization of these systems significantly. The goal of this study is to characterize the hydrogeologic system of the Nashoba Terrane and to propose a conceptual model for this igneous and metamorphic rock aquifer.

1.2.1 Previous Work

O.E. Meinzer (1923) first noted that groundwater yield was lower in wells drilled in crystalline basement rock than in wells drilled in shallower sandstone and surficial aquifers. Meinzer further theorized that this was likely due to both the material and the stress state. He proposed that the permeability of rock would likely decrease with depth due to subsurface stresses. Further studies confirmed a decreased permeability with depth in crystalline rock; data from well yield studies suggested that the network of open joints, which could transport groundwater were principally in the upper 100 to 150 meters of shallow crust (Lagrang, 1954 and 1967; Davis and Turk, 1964). Davis and Turk (1964) further suggested that water-bearing fractures in these crystalline rock systems are primarily controlled by weathering and by structure. It was later proposed that the decrease in permeability with depth, noted in previous studies, was due to decreased abundance and aperture of fractures with depth (Snow, 1969). These were all landmark studies that laid the groundwork for fractured rock hydrogeologic study.

In later years, studies of fractured crystalline aquifers began to focus on the micro-scale. Laboratory studies showed that the permeability of a single fracture was sensitive to applied stresses, such as *in situ* or tectonic stresses (Gangi, 1978; Brace, 1978; Sayer, 1990). If a stress was applied perpendicular to the orientation of the fracture it would close or decrease in permeability. Conversely, if a stress was applied parallel to the fracture orientation the fracture would open or increase in permeability. Several authors have conducted laboratory tests and theoretical analyses, which concluded that fractures were most sensitive to modest stresses of less than 10 MPa (Bandis, 1983; Brown and Schulz, 1986; and Hillis, 1997). These studies noted that fractures would begin to close under very

little stress but that the rate of closure would decrease under greater stresses; this suggests that fracture stiffness increases steadily as the fracture closes.

Pollard and Aydin (1988) proposed that it was necessary to quantify fracture location, direction and genesis in order to fully understand the flow regime of a fractured system, because permeability and effective porosity of a fractured system is not controlled by primary porosity but by secondary porosity. If stress can close or open a fracture based on their relationship in space then knowledge of fracture location should enable quantitative assessment of permeability (Renshaw and Pollard, 1994). This has limits; however, as fracture networks exist in the subsurface where they can not be directly quantified. Authors have proposed that not only were fractures affected by subsurface stresses but that the distribution and orientation of the initial fracture propagation was controlled by subsurface stresses (Barton, 1995 and 1997; Morin and Savage 2004 and 2005). While these assumptions are valid in sandstones, with very predictable fracture trends, they are problematic in crystalline rock where fracture orientation and aperture are anisotropic. Precise measurement of fracture length, aperture and orientation is not possible in this setting. Banks et al. (1992) conducted a fracture mapping survey at an outcrop in a crystalline rock unit and in a recently dug tunnel in the same unit. They found that not only did fracture density decrease with depth but that fractures which appeared to be major conduits for flow at the surface were not present or contributing to flow in the subsurface. This complicates the outcrop mapping technique.

A landmark study was conducted by the USGS at Mirror Lake in New Hampshire to explore groundwater flow in a bedrock setting. This 20 year study focused on identification of fractures and fracture properties at outcrops (Barton, 1996); subsurface structure and hydrogeology using borehole geophysics (Johnson and Dunstan, 1998; Paillet, 1985; and Paillet and Kapucu, 1989); and hydraulic and transport properties of fractures by means of hydraulic testing (Hsieh, 1996; Hsieh and Shapiro, 1996; and Tiedeman and Hsieh, 2001). There were several major findings in this study including: crystalline bedrock does not respond as an equivalent porous media. They further proposed that flow in these rock units occurs in highly transmissive fracture clusters connected by less conductive fractures. They additionally confirmed that the fracture orientations mapped at outcrop were also found in the subsurface.

Harte and Winter (1995) completed a modeling study in which they concluded that flow in the subsurface was affected by overburden, topography as well as fracture anisotropy. Mabee and Hardcastle (1997) suggested that laumontite crystallization in fractures was clogging flow systems, thereby reducing the overall permeability of a rock unit in California.

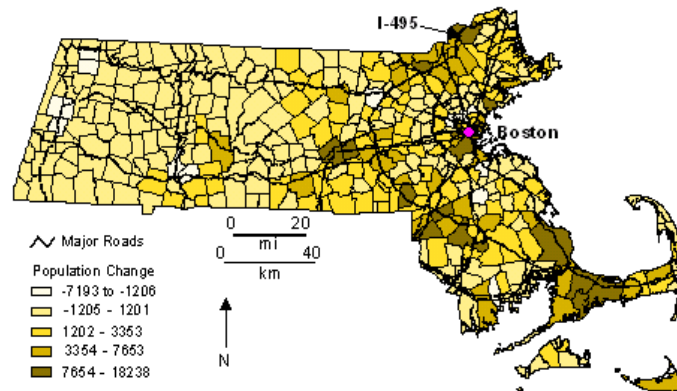
The studies mentioned above focus on fracture flow in the shallow crust. Many of the findings would not apply in the deep crust based on stress and temperature conditions and processes which exist in the deep crust. Ingrebritsen and Manning (1999) analyzed the potential for groundwater flow in the deep crust (below 1 km) and concluded, based on the amount of water necessary for metamorphism, that groundwater must both exist and flow in the deep crust. Additionally, a pumping test was conducted on the 4 km deep KTB test well in Germany. The year long test yielded over 21,000 m³ of saline groundwater; the authors concluded fractures at 2, 3 and 4 km depth are abundant and connected enough for flow

(Stober and Bucher, 2004). Saar and Manga (2004) suggested that fracture abundance would decrease with a power law distribution with depth below 1 km. The resulting fracture frequency with depth is consistent with the results of Ingrebritsen and Manning (1999) as well as Stober and Bucher (2004). It is clear that the depth-permeability relationship first postulated by Meinzer in 1923 is far more complex than previously thought.

Recent studies have again focused on the effect of subsurface stresses on both the micro and macro-scales. Henricksen (2006) suggested, based on field evidence, that fractured bedrock aquifers could be broken into zones based on lineaments. Some studies have focused on hydromechanical coupling (Rutqvist et al., 2003; Rodhe and Bockgard, 2006). Several micro-scale studies have further tested the stress on individual fractures including the stress of a slug test (Svenson, 2007; Schweisinger, 2007), and studies relating hydraulic and mechanical aperture based on applied stress and fracture roughness (Liu, 2005).

1.3 Motivation

In New England, groundwater has traditionally been drawn from surficial aquifer systems, composed primarily of glacial sediments, to meet private, commercial and industrial water needs. Development of new, productive wells in this overburden is constrained by the lack of extensive sand and gravel deposits as well as by the high vulnerability of these units to contamination. Rapid development throughout the region has exacerbated this problem, and the need for better water resource management is great. This is no more evident than in the I-495 corridor of eastern Massachusetts where growth has been staggering (Figure 1). Some communities have experienced population increases of up to 60% in the last 25 years and some have converted as much as 20% of their open space to developed land. The surficial aquifers in eastern Massachusetts can no longer support the water needs of this growing population in many areas. Additionally, recent climate projections suggest that in the coming decade Massachusetts will experience a significant change in the duration and frequency of storm events, with precipitation coming from more extreme and widely spaced events; with low storage in bedrock aquifers this change will likely have a serious affect on the recharge to these systems (NEIA, 2006). Many municipalities are increasingly turning to the deeper, fractured crystalline bedrock aquifer systems to augment their existing water supplies. The need to understand these systems grows ever greater, as a more complete understanding of these bedrock systems will lead to better management in the future.



Figures 1a. Population change in Massachusetts from 1980 to 2000 by town (based on census data available from MassGIS).

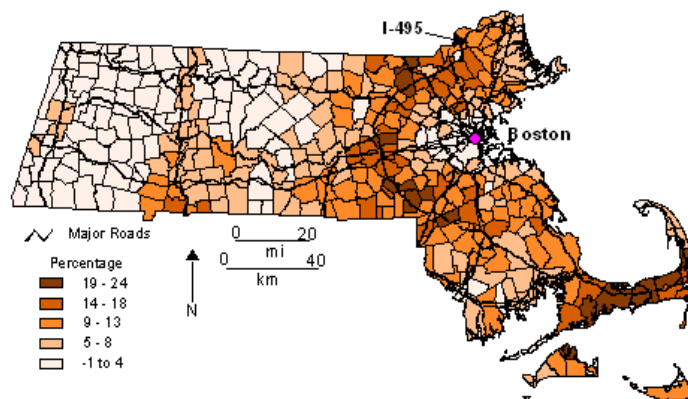


Figure 1b. Percentage of undeveloped land (crops, pastures, forests, and open space), by town, converted to developed land (residential, commercial, industrial land uses, etc.) from 1971 to 1999 (MassGIS, modified from S.B Mabee). Note correlation between growth patterns and major state routes and interstates.

1.4 Geologic Setting

The Nashoba terrane is a fault-bounded block of high-grade, metavolcanic and metasedimentary rock, with extensive igneous intrusions, located in eastern Massachusetts, U.S.A. The Nashoba is northeast trending, extending from the Connecticut border to the Gulf of Maine (Figure 2). The terrane is bounded to the west by the Clinton-Newbury fault zone and to the east by the Bloody Bluff fault zone. The units to the west are largely metasedimentary while the units to the east are predominantly metavolcanic. There are also several large faults throughout the Nashoba Terrane which bound the various units. The following provides a summary of the geologic setting of the Nashoba Terrane (Goldsmith, 1987).

1.4.1 Major units in this study

The Marlboro Formation is primarily composed of interlayered metavolcanic, metavolcaniclastic and metasedimentary rocks. The Marlboro is mostly bounded to the east by the Bloody Bluff fault zone, but was intruded by the Andover Granite. The upper contact of the Marlboro to the west is conformable with the Nashoba Formation. The Marlboro formation has been divided into anywhere from 2 to 31 members. The divisions have been debated but in simple terms there are two sections, the lower section consists of mica schist, calcsilicate rock, marble and amphibolite. The upper section, named the Sandy Pond Member, is predominantly amphibolitic.

The Shawsheen gneiss consists primarily of sillimanitic muscovite-biotite schist and gneiss. It contains layered and massive amphibolite. The Shawsheen is lithologically similar to the Nashoba Formation and has been mapped, by some authors, as part of the Nashoba Formation. It is currently mapped as a separate unit primarily because of the Fish Brook Gneiss which lies between the Shawsheen and the Nashoba Formation.

The Fish Brook gneiss is a fine to medium-grained white to light grey biotite-quartz-plagioclase gneiss. The unit is distinctly foliated but generally unlayered. The foliation is marked by oriented biotite flakes and there are inclusions of amphibolite, thinly layered biotite gneiss and other rocks. The Fish Brook, like the Nashoba Formation is intruded by the Andover Granite. The unit is thought to be either pre-metamorphic intrusive or of sedimentary origin.

The Nashoba Formation is the largest formation of the Nashoba Terrane. It consists of interlayered sillimanite-bearing, partly sulfidic schist and gneiss, biotite-quartz-feldspar gneiss, calc-silicate gneiss and subordinate quartzite and marble. The Nashoba has 13 members, based on lithologic differences. These are described at length by Goldsmith (1987). Only one member has been individually identified on the Massachusetts State map, the Boxford Member. The Boxford member lies in the north of the formation and consists primarily of amphibolite and hornblende-plagioclase schist.

The Tadmuck Brook schist is a primarily a sequence of largely pelitic rocks lying west and presumably above the Nashoba Formation. The unit is primarily composed of sillimanite schist, graphitic staurolite-andalusite phyllite and chlorite-biotite-muscovite

phyllite with decreasing metamorphic grade from east to west. In some areas the Tadmuck Brook intertongues with the Nashoba Formation, however in other areas the unit appears to truncate the Nashoba. The truncation, along with the apparent lack of fault features has led some to believe that the Tadmuck is conformable on the Nashoba.

Two wells in this study were outside the Nashoba Terrane. These wells were located in the Cape Ann Granite which lies south and east of the Bloody Bluff Fault in eastern Massachusetts. The Cape Ann is an unfoliated, medium- to coarse-grained, leucocratic rock ranging in composition from quartzose alkali-feldspar granite through alkali-feldspar quartz syenite. The rock in the area of the wells is alkali-feldspar syenite. The granite ranges in color from pinkish to green to gray depending on weathering and composition. This rock unit is likely Proterozoic in age.

1.4.2 Age of the Nashoba

The stratified rocks of the Nashoba Terrane are unfossiliferous therefore their age can only be inferred from the rocks that intrude them. The upper limits of their age have been established, by phases of the Sharpners Pond diorite, as 430 ± 5 Ma or early Silurian. Radiometric dating in other units suggests an Ordovician age. It is likely that the Nashoba Terrane is Ordovician or possibly Proterozoic in age. The rock units within the terrane are considered to be part of a single lithotectonic entity because common lithologies are interlayered and because the zone is flanked by terranes of disparate lithology structure and metamorphic grade. It is possible, based on age and rock type, that the Nashoba Terrane is Proto-African in origin and was therefore accreted to the North American continent in the early Silurian Goldsmith (1987).

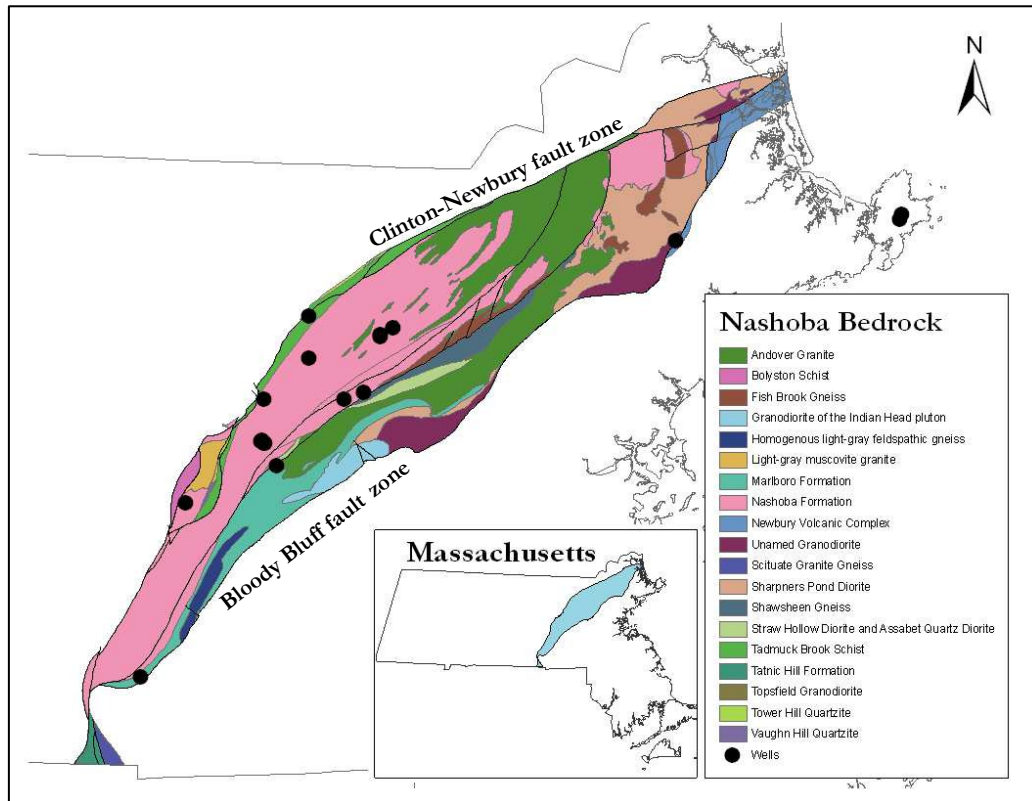


Figure 2. Bedrock Geological Map of the Nashoba Terrane in Eastern Massachusetts, U.S.A. Black dots mark well locations.

1.5 Methods

1.5.1 Borehole Geophysical Logging

A suite of six tools, designed by *ALT* and *Mount Sopris Co*, were used to complete the borehole geophysical investigation of the Nashoba Terrane. The tools are cylindrical, they are between three and twelve feet in length, and they are all approximately three inches in diameter. Each tool is suspended in the borehole using an *ALT* MGX II winch system, which is powered by a generator in the field. The cable is 260 meters long and is connected to the base of each tool by a Gerhardt Conductor. The MGX II logger system is connected, via a USB port, to a laptop computer which receives data during collection. Data is saved, and can be viewed as it is collected using the *Mount Sopris* programs MSLog and MSHeat. The order the tools are used for each survey is very specific and an extensive, step-by-step procedure can be viewed in Appendix A.

The first tool used in the suite is the fluid temperature and resistivity probe (*2PFA-1000*). This tool is used first to gather temperature and fluid resistivity data and it is used as an exploratory probe, to identify obstacles at depth in the borehole. Once the tool is in motion it takes a temperature and fluid resistivity measurement every second for the entire length of the borehole. Generally, as the probe descends the temperature in the borehole increases. Once plotted, the data can reveal some important information about the movement of fluid in the well. For example, if the temperature and/or resistivity of the fluid suddenly shift it is an indication of fluid contribution from a discrete feature. The temperature profile can provide clues as to the path of fluid movement through the borehole from fractures that connect with it. Additionally, the fluid resistivity level can provide a qualitative idea of the residence time of the fluid. In general, the longer the residence time the higher the fluid resistivity due to dissolution of solids from the rock unit into the fluid. Using this data, isolated flow systems can be identified.

The next tool used is the natural gamma probe (*2PGA-1000*). The gamma probe, like the fluid resistivity probe, is light and durable so it is designed to be attached to the fluid resistivity probe. Natural gamma is emitted from three source elements: uranium, thorium, and potassium. Potassium is the most common of these, and is often found in large magnitude in clays. The most common hydrogeologic application of natural gamma is to identify clay-rich layers, which act as confining layers. Application of the natural gamma probe in fractured igneous and metamorphic rock is less useful; however, natural gamma measurements can be used to identify rock type changes at depth. Rock changes are often accompanied by fractures so these measurements can be useful for identifying areas that are more likely to have discrete features that contribute to flow.

The third tool in the suite is the caliper (*2PCA-1000*). The caliper is a three-armed probe which determines borehole diameter. The primary application of the caliper is determining the depth of fractures in the subsurface. When diameter is plotted versus depth the diameter will open where there are fractures (Figure 3). Additionally, the diameter measurements collected by the caliper are used in the calculation of borehole storage.

The fourth tool in the suite is the optical televiewer (*OBI-40*). The optical televiewer (OTV) TV contains a camera which spins in the borehole while taking digital images. The images provide a 360 degree picture of the entire length of the borehole. These images have several important functions. First, the OTV provides an opportunity to study the lithology of the rock unit at depth; this can also aid in verification of the mapped bedrock units. The OTV image is also helpful in identifying fractures in the subsurface. Many fractures are large enough where identification is possible. When viewed in MSLog the complete image is unwrapped into a two dimensional picture. Dipping fractures will appear sinusoidal in two dimensions (Figure 3). A procedure exists to determine the actual orientation of these fractures that will be discussed at length below.

The fifth tool in the borehole geophysical suite is the acoustic televiewer (*FAC-40*). The acoustic televiewer (ATV) creates a two dimensional image of the 360 degree borehole much like the OTV only the image is of rock density. The ATV releases a sonic pulse into the rock unit and then calculates the time and wavelength of the return of that pulse. The ATV produces two density plots one based on wavelength and the other based on return time of the signal. This is the most effective tool for finding discrete fractures and fracture zones in fractured igneous and metamorphic rock. MSLog applies a color scale to rock density such that low density materials are darker than high density materials. Fractures appear quite dark. The ATV has one additional benefit; because the probe measures the density fracture zones emerge where they might not with the caliper and OTV data.

The final tool in the suite is the heat pulse flowmeter (*HPF-2293*). This tool measures the vertical velocity of fluid in the borehole from contributing fractures. To properly use the heat pulse flowmeter it must be used last in the order. The five previous data sets are compiled and areas of interest, which are generally discrete fractures, are identified using these data sets. These areas of interest act as a guide for the heat pulse flowmeter tests. The flowmeter consists of two screened areas near the tip of the tool with a thermistor in the center. The screened areas are isolated from one another with a package of rubber pedals, which act like packers. The flowmeter is placed above the area of interest and the user presses a trigger, which releases a pulse of heat into the screened areas. If there is flow in the well the heat pulse will move with that flow as it passes through the tool and out one of the screens. The flowmeter measures the direction (up or down) and speed of that flow, and calculates the magnitude of the flow in gallons per minute (gpm). Generally three pulses are shot and measured. The flowmeter is then moved below the area of interest and the procedure is repeated. This is done for the entire well from which a flow profile is developed. Then the well is pumped at approximately 0.5 gpm and the test is done again to obtain a profile of the borehole under pumping conditions. Both the ambient and pumping profiles are compiled to identify all flowing fractures.

1.5.2 Processing Geophysical Logs

The program WellCAD was used to process the borehole geophysical logs. The fluid temperature and resistivity, gamma, caliper, OTV and ATV files are imported from MSLog while the heat pulse flowmeter files are imported from MSHeat. During logging, depth error is inevitable so when files are brought into WellCAD they are commonly misaligned. It is essential that files are adjusted to ensure proper alignment so that fracture

depths are accurate; this was done in all cases. Unfortunately, there is no precise way to align the logs in WellCAD, which is a potential source for error when attempting to identify major lithologic changes and fractures. The most accurate way to adjust caliper, OTV and ATV files is to find a large fracture, near the surface that is clearly visible on all the logs; align the logs so that the fracture is aligned on the logs. To properly adjust the temperature and resistivity logs ensure that a water level measurement is taken before logging and adjust the logs according to that measurement. Adjusting a gamma log is significantly more difficult. The best approach to find a major natural gamma shift in the log and attempt to align that with a major lithologic change. In a metamorphic setting, like the Nashoba Terrane, a pegmatite dike is the best rock type to use to make the adjustment.

Finally, the orientation of the OTV and ATV files are not always accurate when imported into WellCAD because the tools spin as they are logging the borehole. The orientation of fractures intersecting the well can be determined as long as the orientation of the log is correct. The OTV and ATV files were then selected in the menu and reoriented to north. This is a vital step as fractures identified in the log will not have an accurate orientation if the log is not oriented properly.

1.5.3 Identifying Fractures

Once all the logs are properly aligned and oriented in WellCAD fractures can be identified and measured. Determining which features are in fact fractures is a difficult process. In this study a fracture was identified if it appears in the ATV or OTV log and the in the caliper log or temperature log. It is vital that fractures are not simply identified from one log (Figure 3).

The ATV file, when viewed in logarithmic scale is the most useful for identifying fractures. As the density difference between solid rock and an open fracture is so extreme, the background of the ATV log will appear yellow and orange and fractures will appear quite dark, even black. Once a fracture was identified in the ATV log, other logs were scanned for evidence of a fracture. Common evidence of a fracture in other logs included: a blip in the caliper log, a matching fracture in the OTV log, a change in lithology seen on the OTV log, or very rarely a shift in temperature or fluid resistivity. Fractures can be labeled by type. In this study three types were catalogued: foliation parallel fractures (FPF), tectonic joints, and subhorizontal unloading joints. Once a fracture is identified the trace is recorded in a structure log file in WellCAD.

The structure data for each well was exported and opened in Microsoft excel. The file contains the depth, strike and dip for each fracture trace. The orientation of the fractures in WellCAD is in dip azimuth, so all fracture orientations were converted to right-hand-rule and plotted on stereonet. This procedure was repeated for all wells in the study.

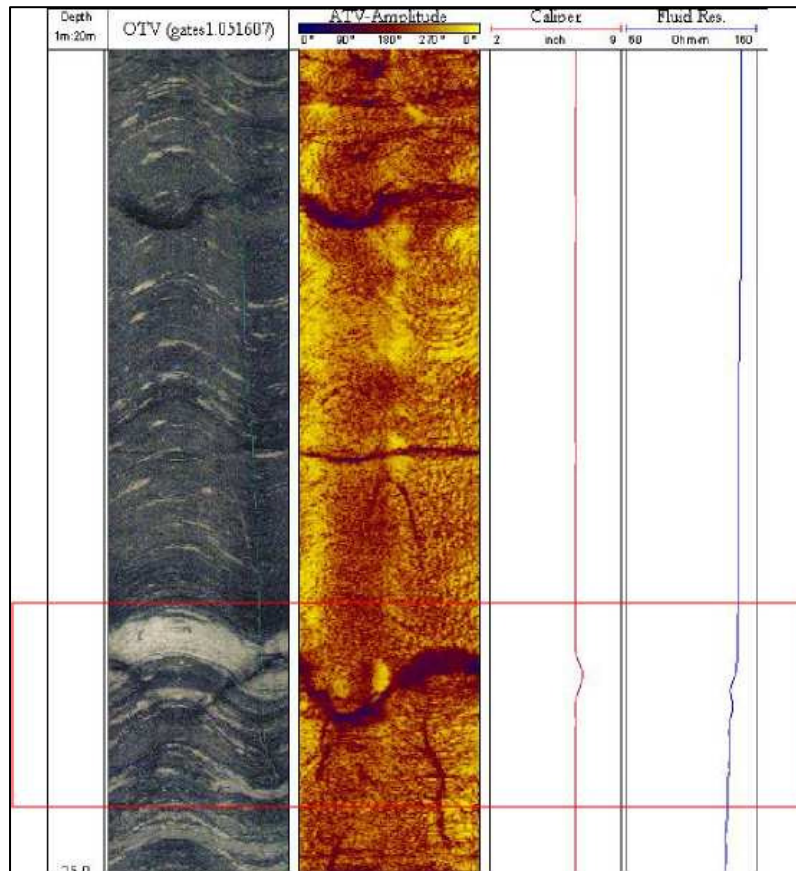


Figure 3. Sample section of a borehole geophysical log from Gates Pond in Berlin, MA. Note the fracture in the ATV and OTV logs corresponding with the fluid resistivity and caliper logs.

1.6 Results and Discussion

1.6.1 Fractures

A total of 1,905 fractures were identified and measured in the seventeen wells studied; a total of 3,108 meters were logged with an average fracture density of 0.64 fractures per meter. The average depth of the studied wells was 179 meters. Manda et al (2008) completed an extensive fracture mapping study of the Nashoba terrane. This study also identified three fracture types present in the terrane: FPF, subhorizontal unloading joints (dip less than 25°), and tectonic joints. The trend direction of the FPF throughout the terrane is approximately 40° (azimuth) with a dip of 70° ; the strike and dip both vary up to $\pm 10^\circ$ (Figure 4). The FPF comprise 40 percent of the total fractures in the terrane (Table 1). The tectonic joints comprise 50 percent of the fractures identified in this study. There are several major tectonic sets including a northwest trending set which is normal to the northeast trending FPF, as well as a north-south trending set and an east-west trending set (Table 1). Subhorizontal unloading joints comprise the remaining ten percent of the fractures in the Nashoba Terrane. Subhorizontal unloading are all joints which dip less than 25° .

It has been proposed that the initial propagation of fractures is related to the tectonic forces at work during that propagation (Barton, 1995 and 1997; Morin and Savage 2004 and 2005). In other words, the orientation of the stress is a factor in determining the orientation of fractures. It is likely then that fractures in the Nashoba Terrane show strong orientation trends because they are related to past tectonic stresses. In every rock type there are prominent north-south and east-west trending fracture sets. These sets are likely related to a past tectonic stress field. The current stress direction in the northeast United States is east-northeast (World Stress Map). The orientation of fracture sets in the Nashoba Terrane suggests that creation of new fractures has been influenced by this stress field. It has also been proposed that subhorizontal unloading joints are related to isostatic rebound following glaciation (Wise, 2005). The crust was compressed during glaciation and the subsequent rebound of the crust caused nearly flat-lying fractures to form.

The Nashoba wells were located in three different rock types. Nine wells are in schist, eight of which are in the Nashoba Formation; five are in amphibolites; and three are in granitic rocks (Table 2). The fracture orientations are broken down by rock type in Figures 7, 8, and 9. There are several prominent fracture sets in the two schist units including northeast trending FPF, east-west trending and north-south trending tectonic joints as well as a subhorizontal unloading joint set (Figure 5). There were several sets identified in the two amphibolite units including a northeast trending FPF set, as well as east-west trending and north-south trending tectonic joint sets (Figure 6). The most prominent set in amphibolite units is a subhorizontal unloading joint set. There were three major sets in the granitic rocks: a north-northeast trending set, a northeast trending set and a north-northwest trending set. There are also two minor sets: an east-west trending set and a northwest trending set. There is no subhorizontal set in wells in granitic rocks (Figure 7). This is surprising as extensive subhorizontal unloading joint sets have been identified in granitic rock before at outcrop (Manda et al., 2008). Lithology is another important factor in determining the orientation of fractures. Weaknesses in the rock units, like microcracks, become fractures and these weaknesses are often related to the structure of the rock type.

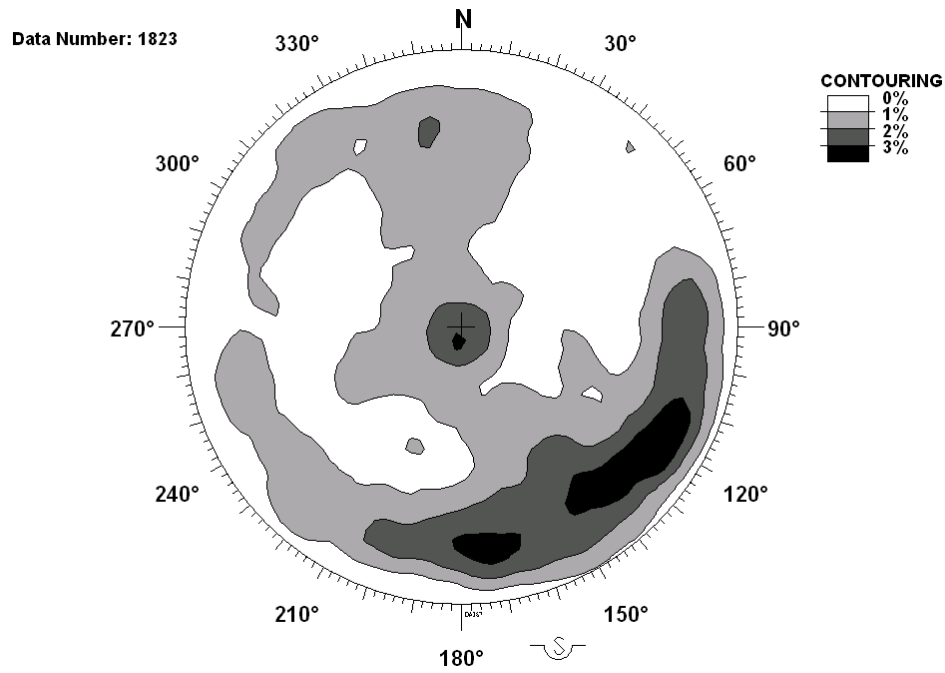


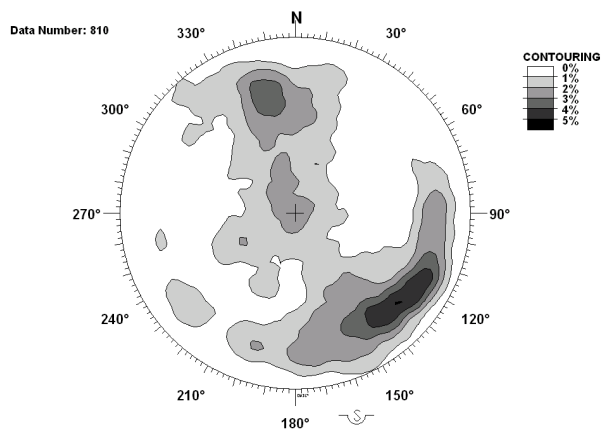
Figure 4. Stereonet of 1,823 fractures measured in wells located in the Nashoba terrane with a 1% contouring interval.

Table 1. Table of fracture types identified in the Nashoba Terrane broken down by major orientation groups.

Fracture Type	Strike, dip (deg)				Percent of Total
FPF	040, 70				40
Tectonic	325, 70	175, 70	265, 65	85, 60	50
Subhorizontal	dip < 25				10

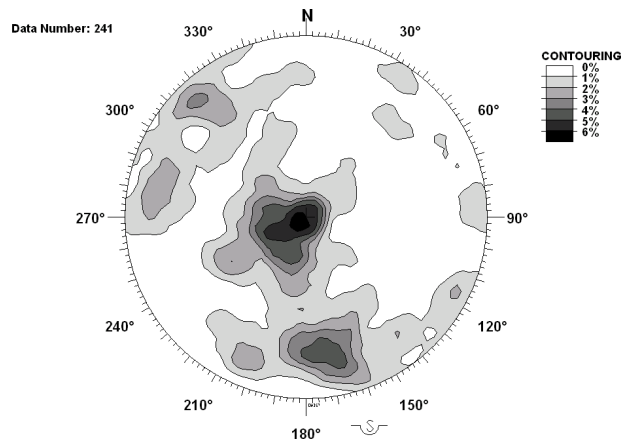
Table 2. Table of the wells studied in the Nashoba Terrane broken down formation name and rocktype

Formation	Rock type	Foliation	Number of Wells
Nashoba	schist	yes	8
Tadmuck Brook	schist	yes	1
unnamed	granodiorite	no	1
Marlboro	amphibolite	yes	3
unnamed	amphibolite	yes	2
Cape Ann	granite	no	2



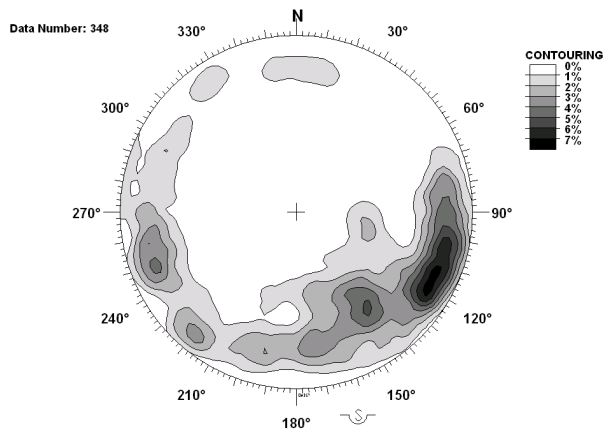
General Trend	Orientation (deg)	Fracture Type
northeast	038, 70	FPF
east-west	080, 60	tectonic
subhorizontal	dip <25	unloading
north-south	180, 70	tectonic

Figure 5. Stereonet of all fractures measured in wells located in Schist bedrock units with a table describing the dominant orientations.



General Trend	Orientation (deg)	Fracture Type
subhorizontal	dip <25	unloading
east-west	265, 65	tectonic
northeast	050, 70	FPF
north-south	015, 65	tectonic

Figure 6. Stereonet of all fractures measured in wells located in Amphibolite bedrock units with table describing dominant orientations.



General Trend	Orientation (deg)	Fracture Type
north-northeast	205, 75	tectonic
northeast	235, 55	tectonic
north-northwest	340, 65	tectonic
east-west	265, 70	tectonic
northwest	310, 75	tectonic

Figure 7. Stereonet of all fractures measured in wells located in Granitic bedrock units with a table of the dominant orientations.

This is evident in the dominant fracture orientations seen in different rock types. FPF are fractures which form along foliation lines which were created as a result of metamorphism. These foliations create weaknesses which result in fracture formation. As a result the northeast trending FPF are extremely common in both Amphibolite and Schist rock units.

1.6.2 Depth Dependence

The frequency of fractures in the Nashoba Terrane decreases with depth (Figure 8 and 9). Figure 8 shows all the fractures measured in the field normalized to consider variable well depth. The shallowest well in the study is 33 meters deep while the deepest well is 380 meters; to account for this variability the fractures were binned in 15 meter intervals and each 15 meter bin was divided by the number of wells that reached that depth. All wells reached 30 meters while only one reached 270 meters. Following this normalizing procedure eliminates the possibility that the depth trend is only due to well depth. On average, 66% of fractures were above 90 meters. Figure 10 shows all fractures broken down by the three fracture types FPF, subhorizontal and tectonic. The data is normalized in the same manner as in Figure 5. The frequency of subhorizontal joints shows no trend with depth while both the FPF and tectonic joints decrease with depth. Both FPF and tectonic joints increase significantly at 180 meters depth.

Figure 8 further suggests that fractures do not decrease at a measurable rate but do so in “plateaus”. In other words, the density of fractures is roughly the same in the upper 60 meters; it drops significantly below that depth and the density is relatively stable between 75 and 180 meters. Finally, the frequency of fractures drops off significantly below 180 meters. It is possible that these “plateaus” are simply an artifact of logging techniques or the normalization technique used in the figure. It is equally possible, however, that bedrock responds to *in situ* stress in a consistent way with depth. There is also a significant increase in the density of both tectonic joints and FPF at approximately 180 meters depth (Figure 9). Further analysis of these results shows that this spike is primarily due to two wells which have unusually high fracture density at this depth. One of the wells, in Maynard, MA, is extremely productive (60 gpm). This well is part of a suite of high yield public water supply wells. It has been proposed that these wells have high yield because of a previously unmapped fault zone in the area (Walsh, 2001). It is possible that the high fracture density at that depth is related to the fault zone. The other well, in Boxborough, MA, yields less than 0.5 gpm and is near no known fault. Due to the disparate nature of these wells no conclusion can be drawn from this anomaly.

1.6.3 Fracture Flow

A total of 73 fractures were found to be contributing to flow in the boreholes, which is four percent of the total fractures measured. There are several fracture orientation sets amongst the flowing fractures in the Nashoba terrane including a subhorizontal set, a northeast trending FPF set, as well as northwest trending, east-west trending and north-south trending tectonic joint sets (Table 3, Figures 10). Of the flowing fractures 32 percent are FPF, 17 percent are subhorizontal and the remaining 51 percent are tectonic joints. Results suggest that subhorizontal unloading joints have an important role in the transmission of fluids. Figure 11 is a stereonet of flowing fractures in schist. There are

several sets including a significant subhorizontal unloading joint set, a northeast trending FPF set, and east-west and north-south trending tectonic sets. Figure 12 is a stereonet of flowing fractures in amphibolites. There are three dominant sets: a significant subhorizontal unloading joint set, a northeast trending FPF, and an east-west trending tectonic joint set.

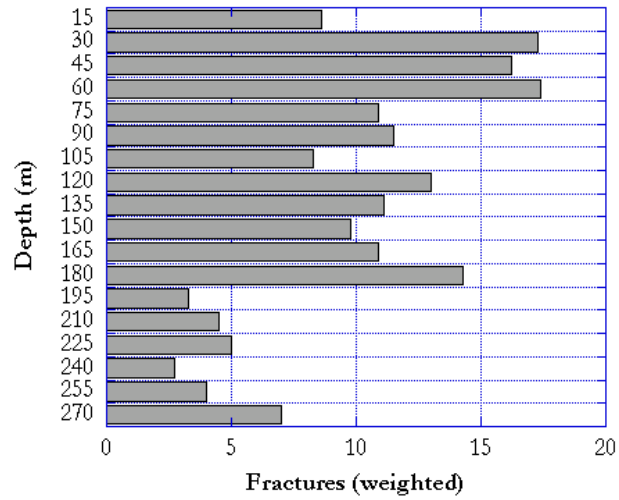


Figure 8. Histogram of fractures with depth, weighted to consider variable well depth.

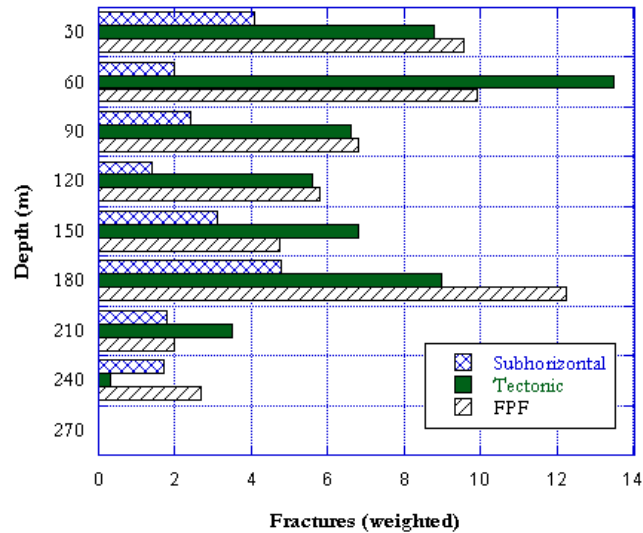


Figure 9. Histogram of fractures with depth broken down by the three fracture types FPF, subhorizontal and Tectonic. Plot is weighted to consider well depth.

Table 3. Table of dominant orientation sets of flowing fractures in the Nashoba Terrane.

General Trend	Orientation (deg)	Fracture Type
subhorizontal	dip <25	unloading
northeast	030, 60	FPF
northwest	330, 40	tectonic
east-west	260, 60	tectonic
north-south	010, 75	tectonic

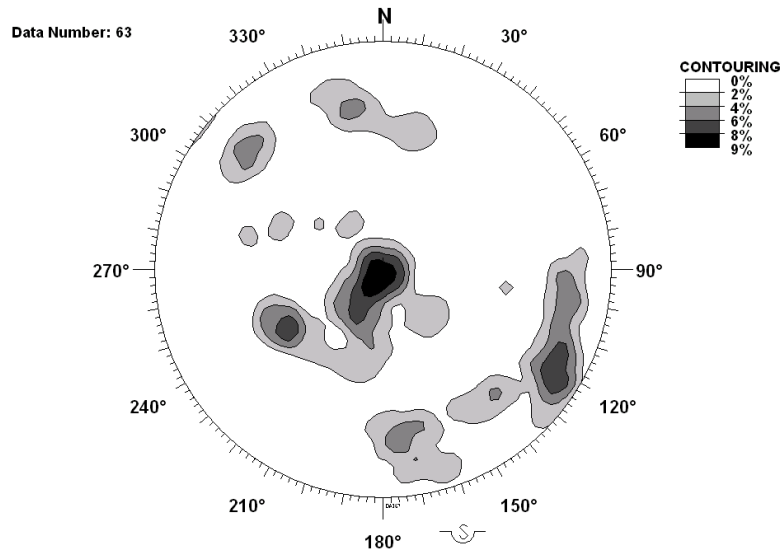


Figure 10. Stereonet of all flowing fractures measured in the field with a 1% contour interval.

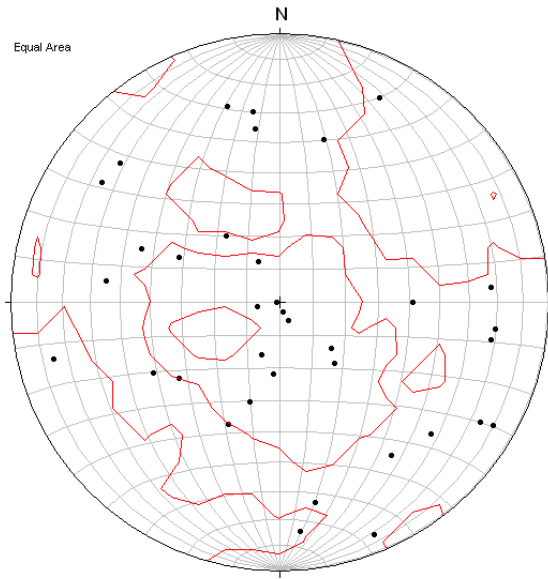


Figure 11. Kamb contour plot of flowing fractures in wells located in schist (n=36).

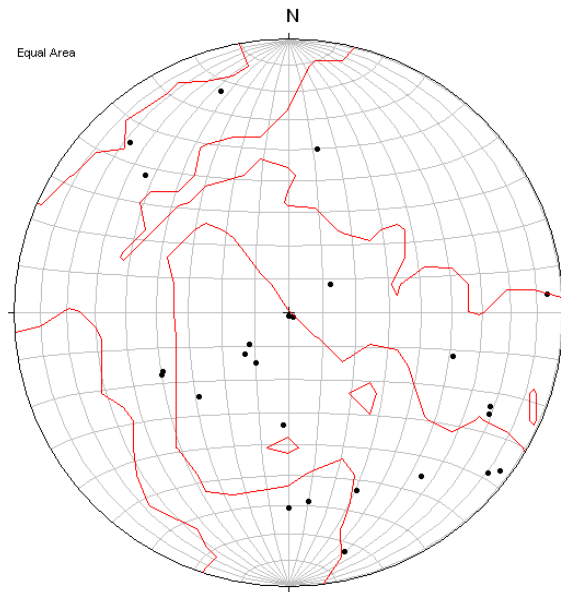


Figure 12. Kamb contour plot of flowing fractures in wells located in amphibolite (n=24).

Figure 13 is a stereonet plot of flowing fractures in granite. In granite there is a north-northeast trending set, and a north-south trending set. There are no subhorizontal unloading joints contributing to flow in granitic rocks.

The current stress direction in the northeast United States is east-northeast (World Stress Map); and studies have suggested that fractures which are optimally oriented to the stress direction would likely have a larger aperture (Gangi, 1978; Brace, 1978; Sayer, 1990). Based on that premise the subhorizontal, east-west trending tectonic joints and the northeast trending fractures should have larger apertures. A larger aperture would allow more fluid transmission. It is reasonable to assume that these “optimally oriented” fractures would be more likely to transmit fluid. Further analysis of fracture data suggests that orientation of fractures has little influence on the magnitude of flow through them (Figure 14). Though subhorizontal unloading joints appear to play an important role in fluid transmission the dip of a fracture does not appear to have an influence on the magnitude of flow from them. Figure 15 is a plot of fracture dip versus the magnitude of flow; no real trend between dip and flow emerges in this plot.

1.6.4 Depth and Flow

The frequency of flowing fractures decreases with depth and while there are available fractures no flow was found below 170 meters (Figure 16). There is also very little flow below 100 meters. Figure 17 is a histogram of flowing fractures in the Nashoba Terrane broken down by fracture type. The frequency of flowing tectonic and FPF joints decreases with depth as seen in Figure 13. The subhorizontal fractures do not decrease with depth but do not flow at all below 100 meters. Additionally, the magnitude of flow from fractures decreases significantly with depth (Figure 18 and 19). The magnitude of flow from fractures in the upper hundred meters varies from less than 0.01 L/sec to 0.55 L/sec. Below 100 meters there is not fracture flow greater than 0.01 L/sec.

The relationship between flow and depth is likely to be the result of *in situ* stress on fracture permeability. Fractures are less likely to form, and have apertures large enough to transmit groundwater, with depth in bedrock environments (Legrand, 1954 and 1967; Davis and Turk, 1964). Recent studies have shown that flow can exist at depths as deep as 4 km and that flow would be necessary for metamorphism in tectonic environments (Stober and Bucher, 2004, Ingebritsen and Manning, 1999). Groundwater found in these deep aquifers is always saline and is likely to be residual groundwater and not the result meteoric recharge. For use as a drinking water source, it is a relevant assumption that groundwater flow will decrease with depth in the shallow crust. Results from this study show that a vast majority of flow in the Nashoba terrane is constrained to the upper 100 meters. Values similar to this have been proposed before (Legrand, 1954 and 1967; Davis and Turk, 1964). Figures 15 and 16 show that the number of flowing fractures, as well as the magnitude of flow from those fractures, decreases significantly below 100 meters. Temperature profiles from all the wells also show little to no influence of fracture flow below 100 meters (Figure 8). It is likely that the reduction in fracture frequency decreases connectivity in the rock. The primary porosity of the rock types found the Nashoba terrane is virtually zero so a reduction in fracture connectivity would restrict regional flow. It is also probable that *in situ* stress at depth reduced the permeability of individual fractures as well. This is evidenced by the significant reduction in the magnitude of flow below 100 meters.

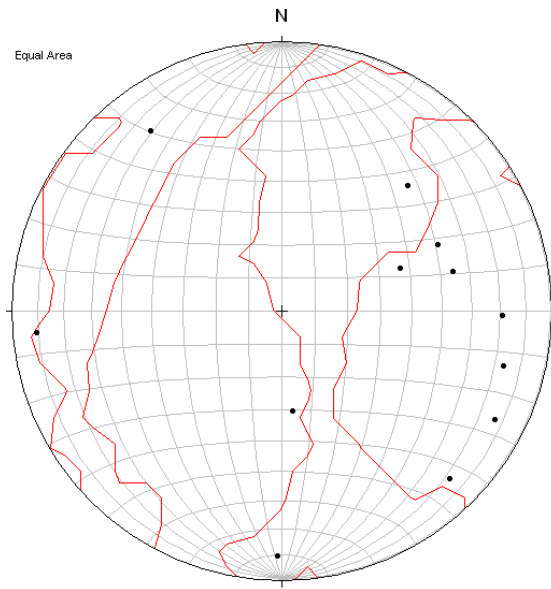


Figure 13. Kamb contour plot of flowing fractures in wells located in granitic rocks (n=11).

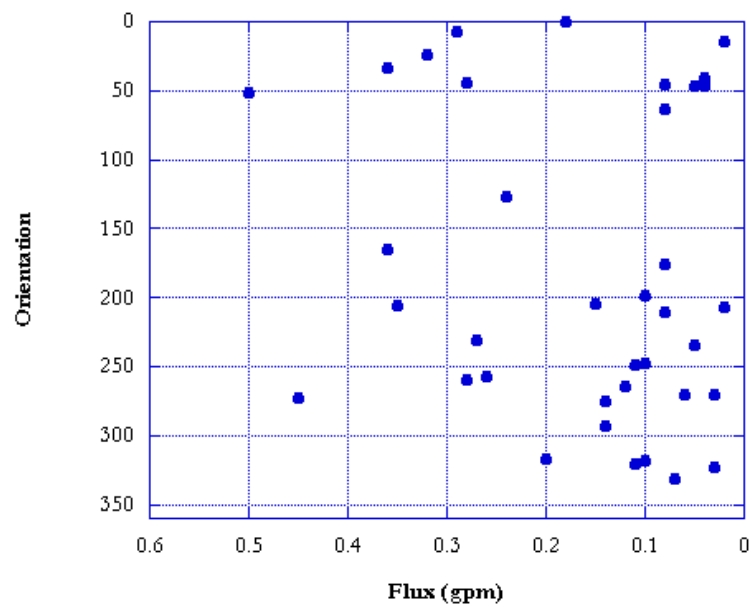


Figure 14. Scatter plot of fracture strike versus the flux of flow in fractures (gallons per minute).

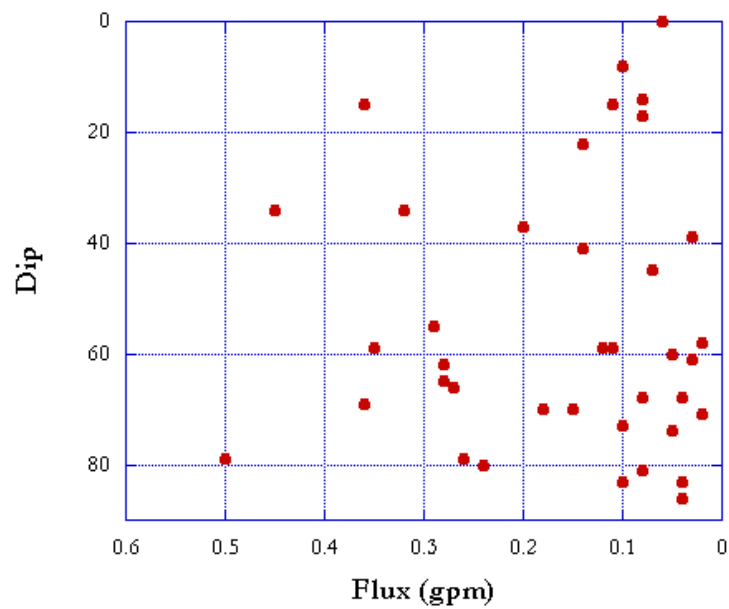


Figure 15. Scatter plot of fracture dip versus the flux of flow in fractures (gallons per minute).

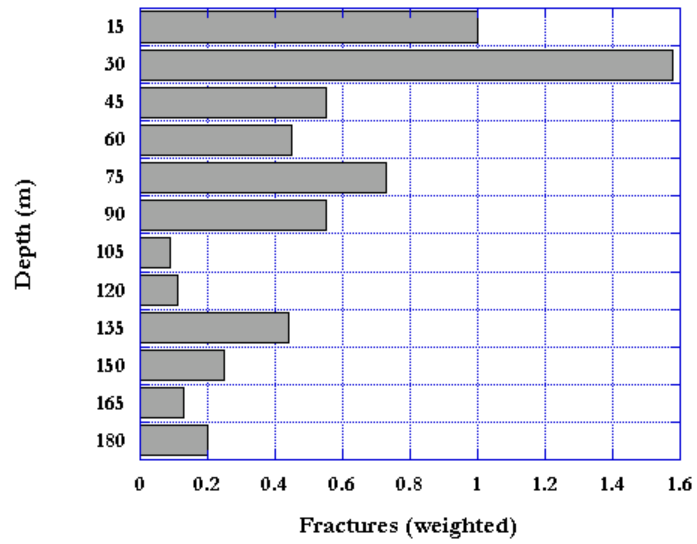


Figure 16. Histogram of flowing fractures with depth. Fractures weighted to consider variable well depth.

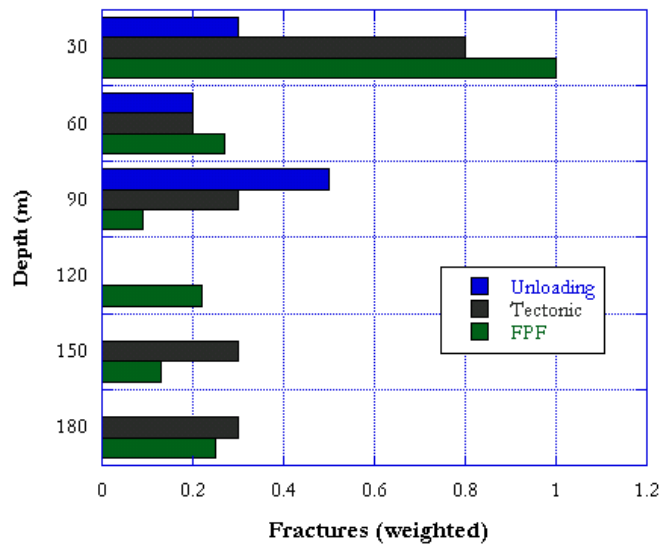


Figure 17. Plot of flowing fractures versus depth in all Nashoba wells. Plot weighted to consider variable well depth.

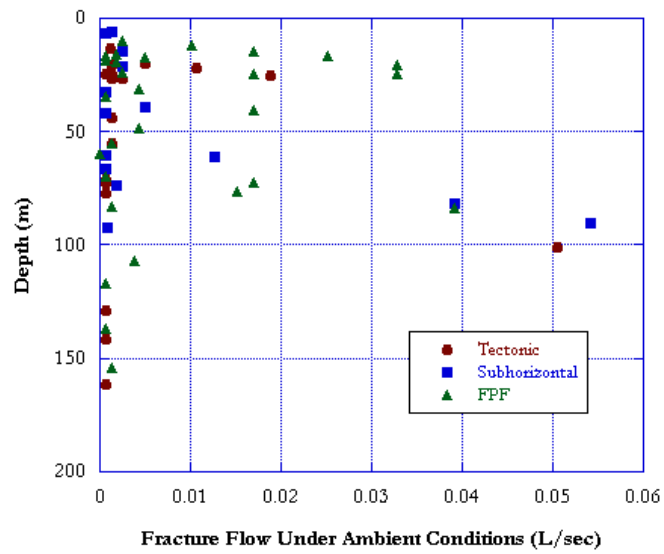


Figure 18. Scatter plot of the magnitude of flow in fractures under ambient conditions. Points are broken down by fracture type.

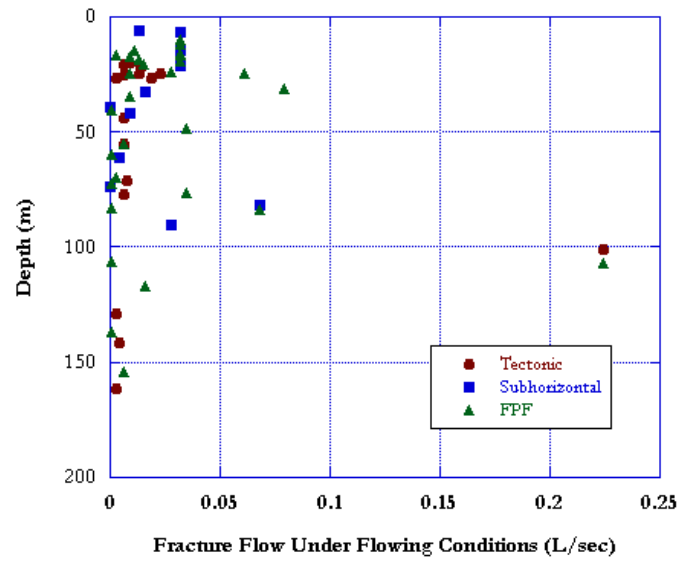


Figure 19. Scatter plot of the magnitude of flow fractures under pumping conditions. Points are broken down by fracture type.

There are no flowing subhorizontal fractures below 100 meters depth (Figure 10). These results further suggest important role of subhorizontal unloading joints in the transmission of fluids. It is possible that subhorizontal unloading joints, which exist below 100 meters, do not have large enough aperture to transmit fluid. Cushman et al. (1993) put forward that subhorizontal unloading joints were not likely to exist at all below 300 meters. Equipment and well availability did allow logging at this depth. It has been proposed that the initial propagation of fractures is related to the tectonic forces at work during that propagation (Barton, 1995 and 1997; Morin and Savage 2004 and 2005). In other words, the orientation of the stress is a factor in determining the orientation of fractures. It is likely then that fractures in the Nashoba Terrane show strong orientation trends because they are related to past tectonic stresses. Tectonic joints have several common orientations including east-northeast trending, north-south trending, and east-west trending. The current stress direction in the northeast United States is east-northeast (World Stress Map). The orientation of fracture sets in the Nashoba Terrane suggests that they are influenced by this stress field.

1.6. 5 Specific Capacity, Hydraulic Conductivity and Transmissivity

Drawdown data from pumping tests at each well is used to calculate the specific capacity (SC) hydraulic conductivity (K) and the transmissivity (T) of each well using the Cooper-Jacob method (1946). The Equation is:

$$SC = Q/S_w \quad (1)$$

Q is constant discharge (m^3/sec) and S_w is drawdown. T can be calculated from SC using equation 2. Here t is time (sec), r_w is the pumped well radius (m), and S is the dimensionless storativity value.

$$SC = \frac{T}{0.183 \log (2.25 Tt/r_w^2 S)} \quad (2)$$

Assuming certain standard values for T (30,000 US gal/day/ft), S (0.001 for a confined aquifer or 0.075 for an unconfined aquifer), r_w (0.5 ft), and t (1 day), Batu (1999) developed simplified equations for T using SC for a confined aquifer (Eq. 3) and an unconfined aquifer (Eq. 4):

$$T = 1.385(SC) \quad (3)$$

$$T = 1.042(SC) \quad (4)$$

From these equations a borehole hydraulic conductivity (K) can be derived using the equation 5 where b is the unit thickness defined as the length of saturated borehole below the casing.

$$K = T/b \quad (5)$$

The results of these calculations are in Table 4 below. Based on the above assumptions, the average T for the Nashoba wells is 7.4E +01 (m²/day), the average K is 3.442E -01 (m/day) or 3.983E -06 (m/sec).

Table 4. Estimation of Specific Capacity (SC) Transmissivity (T) and Hydraulic Conductivity (K) for selected Nashoba boreholes.

Well	Rock type	Thickness (m)	SC (m ² /day)	T (m ² /day) unconfined	K (m/day)	K (m/sec)
act1	Schist	145	1.29E+00	1.51E+02	8.80E-03	1.02E-07
act2	Schist	177	6.86E+00	1.85E+02	3.94E-02	4.56E-07
box1	Schist	171	4.52E-01	1.78E+02	2.57E-03	2.98E-08
gates1	Schist	172	1.33E+00	1.79E+02	7.72E-03	8.93E-08
gates2	Schist	235	9.93E+00	2.45E+02	4.28E-02	4.95E-07
gates3	Schist	237	2.36E+01	2.47E+02	1.01E-01	1.17E-06
har1	Schist	164	7.97E+00	1.71E+02	4.87E-02	5.63E-07
may2	Amphibolite	168	2.36E+01	1.75E+02	1.35E-01	1.56E-06
nor1	Amphibolite	26	1.99E+00	2.67E+01	6.88E-02	7.97E-07
roc1	Granite	128	1.22E+02	1.33E+02	9.32E-01	1.08E-05
roc2	Granite	155	5.40E+02	1.62E+02	3.36E+00	3.89E-05
shr1	Amphibolite	201	2.54E+00	2.10E+02	1.24E-02	1.43E-07
sto1	Amphibolite	81	4.59E+00	8.48E+01	5.21E-02	6.03E-07
sut1	Amphibolite	225	1.77E+00	2.35E+02	7.98E-03	9.23E-08

1.8 Conclusions

Three fracture types were identified in the Nashoba Terrane: foliation parallel fractures (40%), tectonic joints (50%) and subhorizontal unloading joints (10%). Additionally, several fracture orientation sets were identified. These include east-west trending, north-south trending and northwest trending tectonic joints. The seventeen wells logged for this project were in three rock types: schist, amphibolite and granite. Dominant fracture sets differ in these three rock types primarily due to their variable lithologies. Wells logged in schist were dominated by northeast trending foliation parallel fractures and subhorizontal unloading joints; wells in amphibolite were dominated by subhorizontal unloading joints and east-west trending tectonic joints; wells in granitic rock were dominated by east-west trending, north-south trending and northeast trending tectonic joints. The frequency of fractures decreases with depth in the Nashoba terrane, however, no measurable trend for this decrease was identified.

Only 4% of the total fractures identified contributed to flow in boreholes. A majority of flowing fractures were subhorizontal unloading joints, northeast trending foliation parallel fractures and east-west and north-south trending tectonic joints. Study results suggest that the orientation of a fracture does determine whether or not it transmits groundwater, however results also suggest that subhorizontal unloading joints play an important role in the transmission of groundwater on a regional scale. Rock type also has little influence on the productivity of fractures or wells. It is likely then that fracture connectivity and topography determine which fractures transmit fluid.

Fracture frequency data, along with heat pulse flowmeter results show that the frequency of flowing fractures decreases dramatically with depth in the Nashoba Terrane. No flow was measured below 170 meters below ground surface. Fracture type analysis revealed that there are no subhorizontal unloading joints below 100 meters which suggests that flow in the Nashoba is affected by the presence and aperture of subhorizontal fractures.

Use of the Nashoba terrane as a private and municipal groundwater resource will likely continue to grow in the future, and proper use of the aquifer will be essential to its sustainable, long-term use. The results of this study will be a helpful resource for when considering a water use plan. Flow occurs in connected networks of roughly four percent of the total fractures and regional flow in the Nashoba Terrane is largely constrained to the upper 100 meters of the bedrock. Therefore wells are most likely to produce sustainable groundwater in the upper 100 meters. Many wells drilled in this bedrock unit will be low yield (between one and five gallons per minute) and very few will be high yielding (more than 100 gallons per minute). Additionally, the rate of recharge into the Nashoba terrane is not known. Serious consideration of the cost and potential benefits should be undertaken before any well is drilled deeper.

1.9 Well Reports

1.9.1 NARA Acton, MA

The ID for this well is act1.072407. It was logged from July 24, 2007 through July 27, 2007. The NARA, or North Acton Recreational Area, is a public recreation facility along Rte 119 in Acton, MA (Figure 20). The site is approximately 56 meters above sea level. The well sits along an athletic field approximately 100 meters from a man made pond. There are outcrops of bedrock approximately 25 meters from the well. The well was drilled as part of a suite of wells which are used for watering the athletic fields. Of the three wells drilled act1.072407 had the lowest yield so it is unused. The other two wells, one of which is less than 25 meters away are currently in use. They were not, however, in use during logging.

Approximately three meters of glacial till overburden at the site. The till is composed of nonsorted, unstratified matrix of sand with small amounts of silt and clay. There are scattered cobbles and a few small boulders. The well is cased in bedrock. The bedrock unit is the Nashoba formation. It is a fine to medium grained and well foliated, gray to silvery-gray quartz-mica schist that may contain biotite, garnet and sillimanite.

The well is 152 meters deep with 7.6 meters of casing. There were 25 fractures identified and measured. They were primarily subhorizontal unloading joints and northeast trending FPF. The frequency of fractures decreased significantly with depth (Figure 21). There are two primary orientations at this site: northeast trending foliation parallel fractures and subhorizontal unloading joints (Figure 22). This is generally consistent with the trend of fracture orientations in the Nashoba terrane; however it is not consistent with the nearest outcrop measurements which show a strong northwest trending set of tectonic joints (Figure 23). This is likely a result of the small number and steep dip of the northwest trending fractures in the Nashoba Terrane. Steeply dipping fractures are under-sampled in a vertical borehole.

The water table was at 5.46 meters depth. Heat pulse flowmeter measurements were taken under ambient and pumping conditions at this well. The well was pumped at a rate of $\frac{1}{2}$ gallon per minute (gpm) for approximately two hours 50 minutes. Of the twenty five measured fractures two were contributing flow to the borehole, which is eight percent of the total. The depths of the flowing fractures are 24 (24°, 34°) and 70 (293°, 41°) meters (Figure 24).

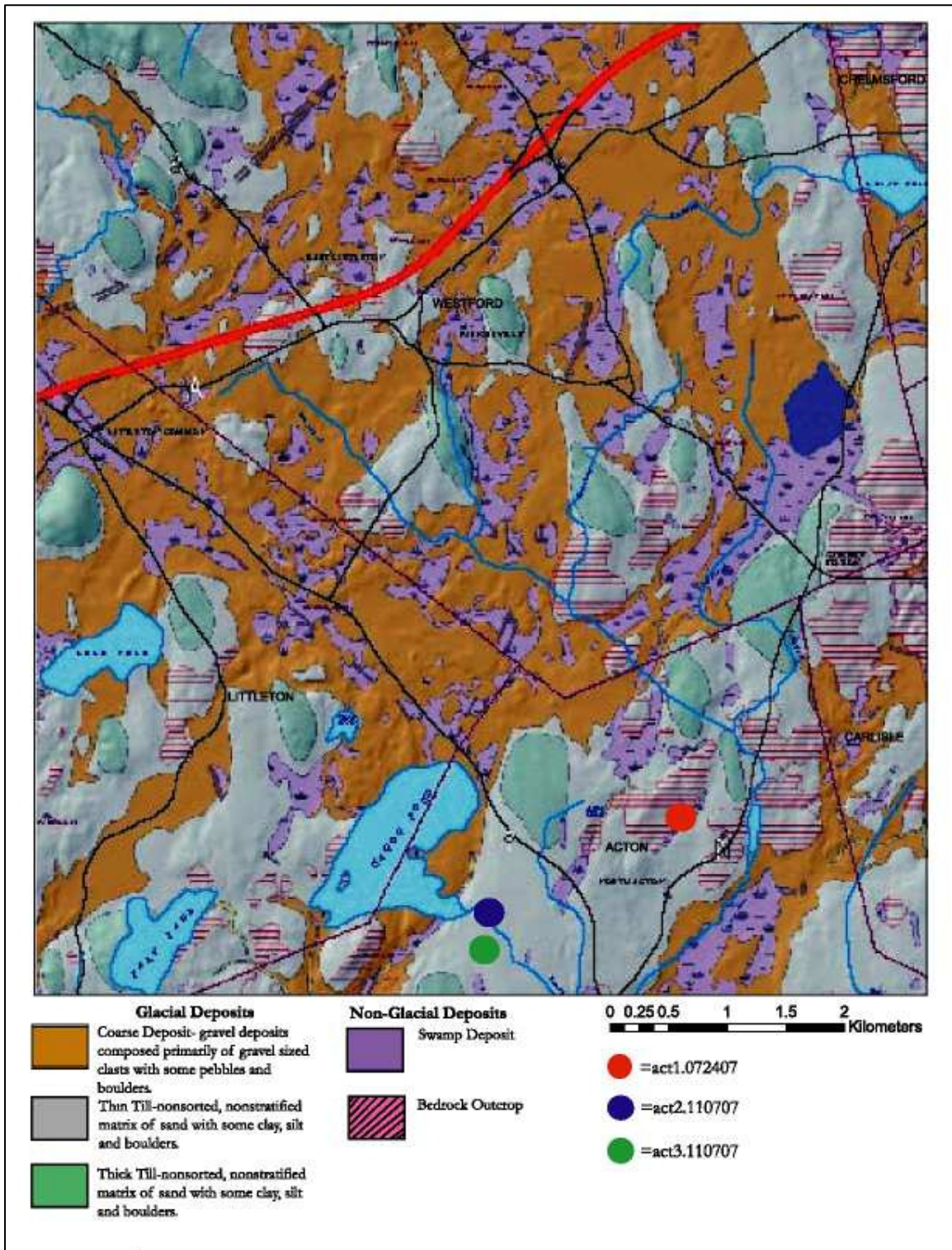


Figure 20. Surficial map of the Acton, MA area derived from the Hudson Quadrangle, Massachusetts (Stone and Stone, 2006).

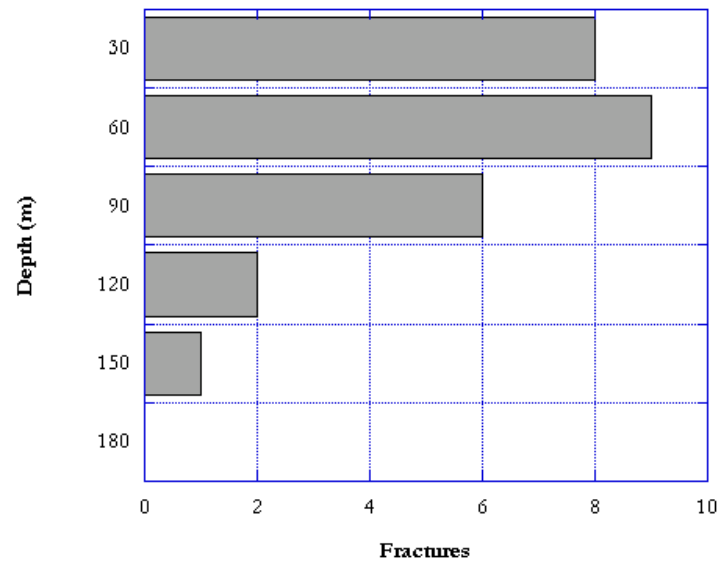


Figure 21. Histogram of fractures versus depth in the act1.072407 well.

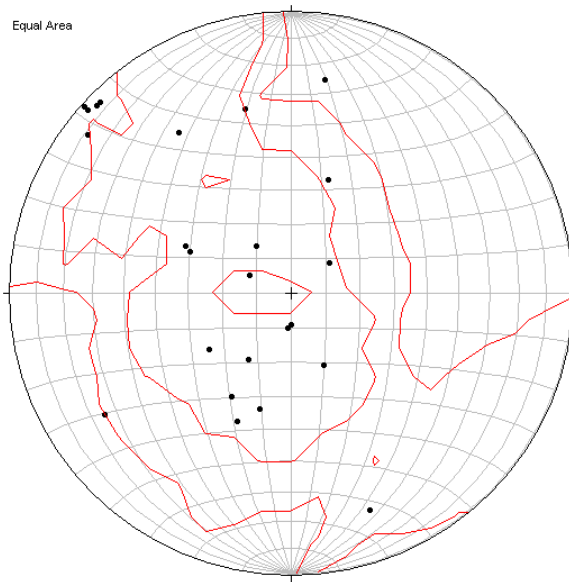


Figure 22. Kamb Contour plot of fracture orientations in the act1.072407 borehole (n=25).

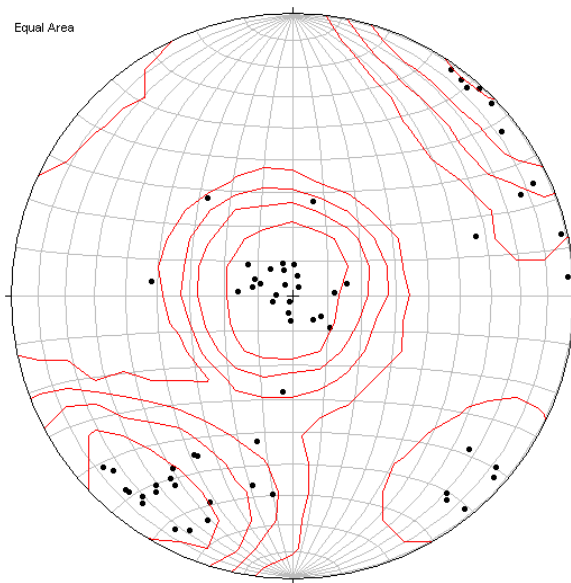


Figure 23. Kamb contour plot of fractures measured at outcrop "wf0447" in the Nashoba Formation (n=63).

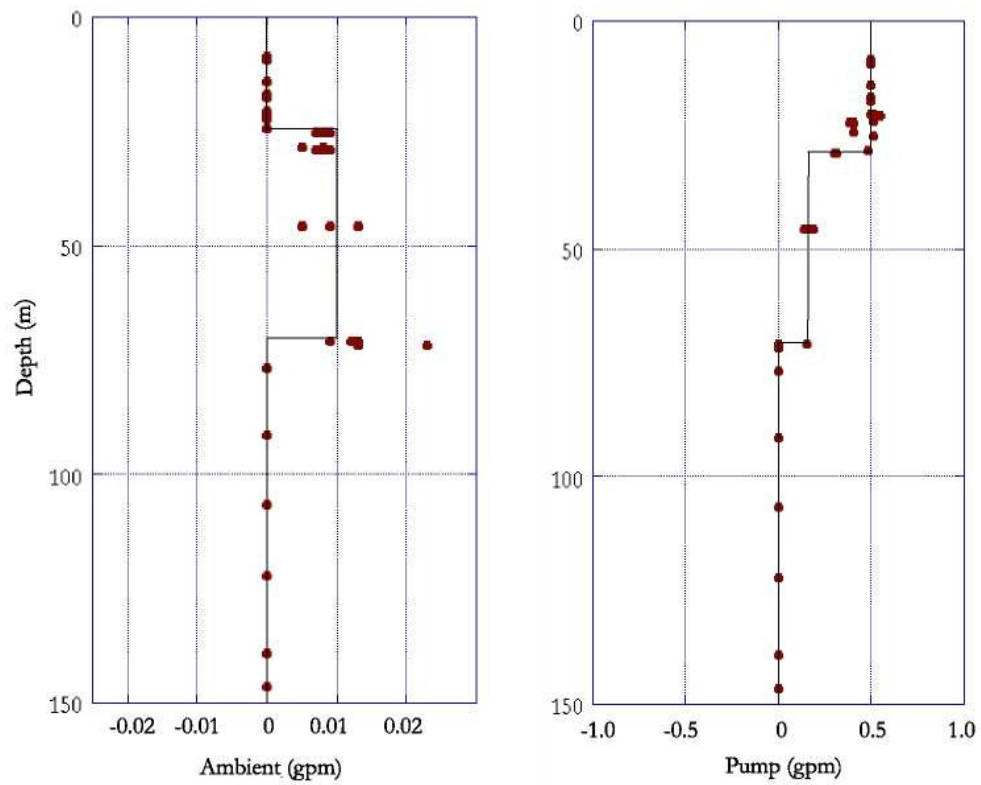


Figure 24. Plot of borehole flow profile from act1.072407. Data collected using Heat Pulse flowmeter.

1.9.2 Quayle Ridge Golf Club Acton, MA

The Quayle Ridge Golf Club is located at the intersection of Routes 119 and 3A in Acton, MA at approximately 50 meters above sea level. A suite of bedrock wells were drilled for course maintenance; of these two have been left unused due to low yield which was estimated at two gallons per minute by the drillers. The two low yield wells on the course were logged on this site. Their ID numbers are act2.110707 and act3.110707. They are located approximately one half mile apart. The wells were logged for a total of four days spread over several months, between November 7, 2007 and May 14, 2008.

The overburden at both wells is glacial till (Figure 20). The till is composed of nonsorted, unstratified matrix of sand with small amounts of silt and clay. There are scattered clasts and few small boulders. It is likely however that all the natural overburden was removed when the golf course was constructed. The bedrock unit is the Nashoba formation. It is a fine to medium grained, and well foliated, gray to silvery-gray quartz-mica schist that may contain biotite, garnet and sillimanite.

Act2.110707 The act2.110707 well is 181 meters deep and has 3.6 meters of casing and there is virtually no overburden. There were a total of 35 fractures identified in this well. The frequency of fractures decreases significantly with depth in the well (Figure 25). Of the total fractures seven are FPF, eight are subhorizontal unloading joints and 20 are tectonic joints. There are four primary orientation trends in the well: Northeast striking (FPF), shallow (unloading), east-west trending and northwest striking tectonic joint (Figure 26). These trends are comparable to the trends seen in the fractures measured at the nearest outcrop (figure 27). The outcrop data showed strong subhorizontal trends with northeast and northwest striking fracture sets.

The water table depth in the well averaged 11 meters during the study. HPFM was done on the well under ambient and pumping conditions. The well pumped for a total of two hours fourteen minutes during which time the well was drawn down 0.35 meters. Of the total fractures measured in the act2.110707 well four fractures were contributing to flow in the well, which is 11% of all fractures. Of the flowing fractures one was a subhorizontal unloading joint and the remaining three were tectonic joints. Flowing fractures were at 6.2 (349°, 7°), 24.7 (51°, 26°), 55.5 (180°, 41°), and 82.8 (265°, 75°) meters depth in the well (Figure 28).

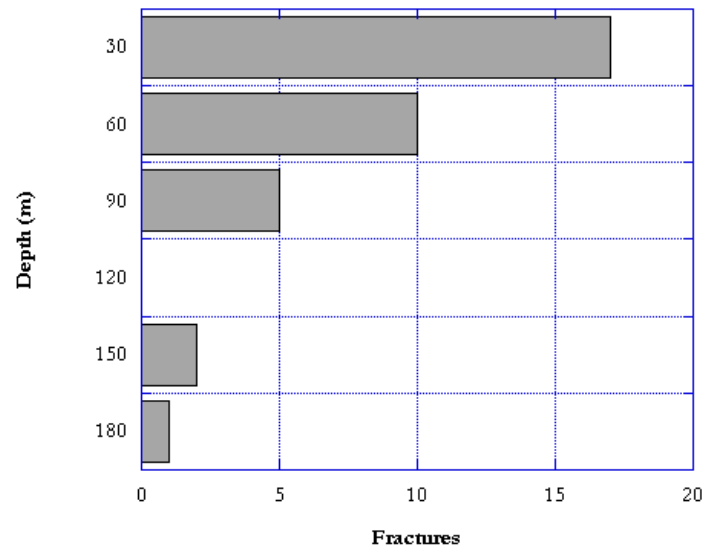


Figure 25. Histogram of fractures versus depth in the act2.110707 well.

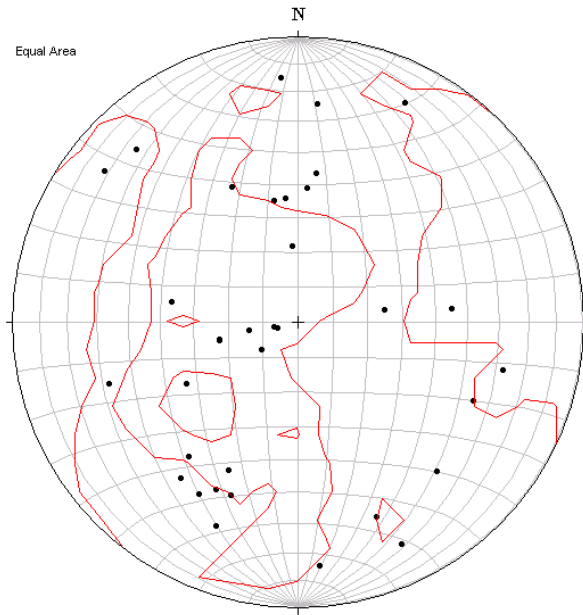


Figure 26. Kamb contour plot of fractures measured in act2.110707 (n=86).

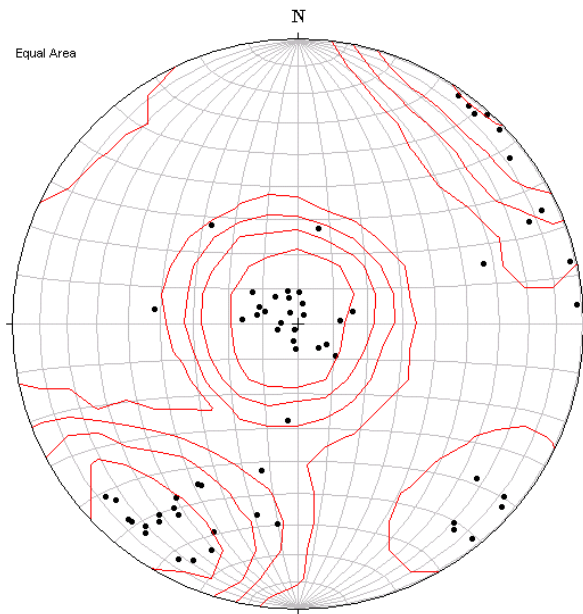


Figure 27. Kamb contour plot of fractures measured at outcrop “wf0447” in the Nashoba Formation (n=63).

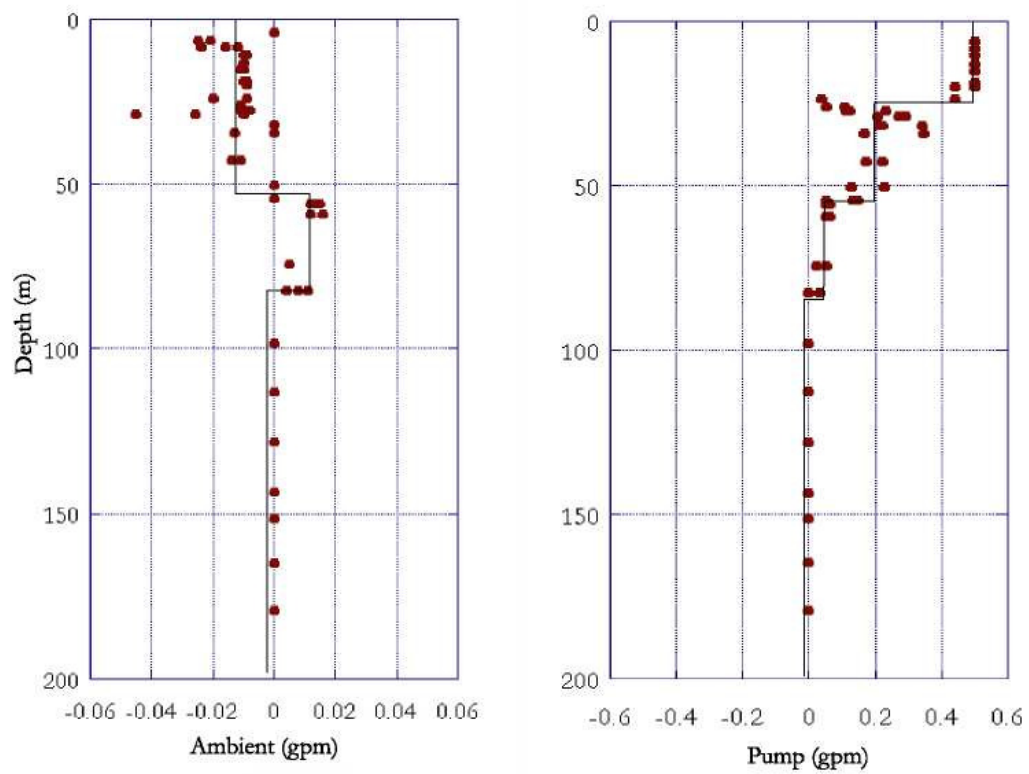


Figure 28. Plot of borehole flow profile from act2.110707. Data collected using Heat Pulse flowmeter.

Act3.110707 The act3.110707 well is 67 meters deep with 5.6 meters of casing. There is approximately one meter of overburden, consisting of artificial fill. A total of 19 fractures were identified in this well. There is no real decrease in fracture frequency with depth probably due to the shallowness of the well (figure 29). Of the total fractures identified four are FPF, two are subhorizontal unloading joints and the remaining ten are tectonic joints. There are two major fracture sets present in this well a subhorizontal set and a northeast trending FPF set (Figure 30). This is generally comparable to the fracture sets identified at the nearest outcrop (Figure 31). The well data lacks a northwest trending tectonic set, similar to the act1.072407 well. This is likely because steeply dipping tectonic joints are under-sampled in the borehole. The steeper the dip the less likely the fracture is to intersect a vertical borehole.

The water table in November, 2007 was at 35 meters depth in this well, which is extremely low. A pumping well is located approximately 15 meters away and likely lowered the water level over the course of the spring and summer. This is supported by the water table measurements taken at the well the following spring when the water table rose to a depth of five meters in May, 2008. Only HPFM ambient tests were run due to the low water table in the fall. The depth of the water was beyond the limits of the pumping apparatus. During the ambient test one fracture at 66 meters (278°, 25°) was identified as a flowing fracture (Figure 32). This fracture was a subhorizontal unloading joint. The low dip angle of this fracture is further evidence of the connectedness of this well with the nearby pumping well, as the subhorizontal joints commonly have trace lengths that extend several meters (Manda et al., 2008).

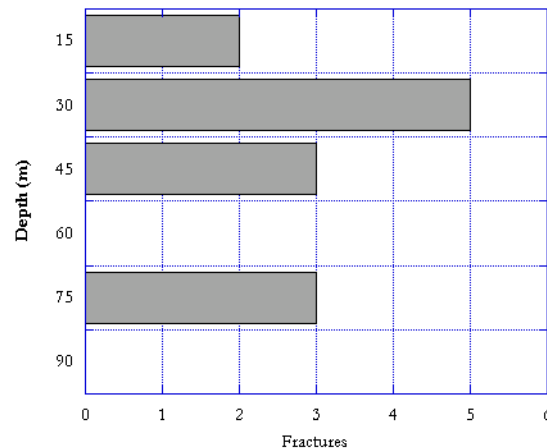


Figure 29. Histogram of fractures versus depth in the act3.110707 well.

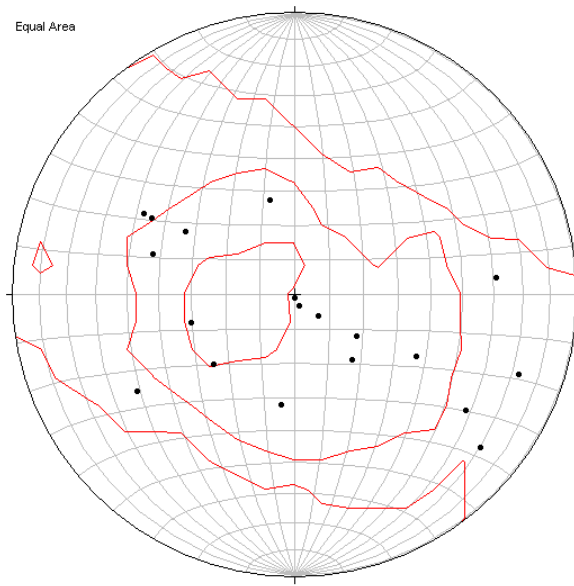


Figure 30. Kamb contour plot of fractures measured in act3.110707 (n=19).

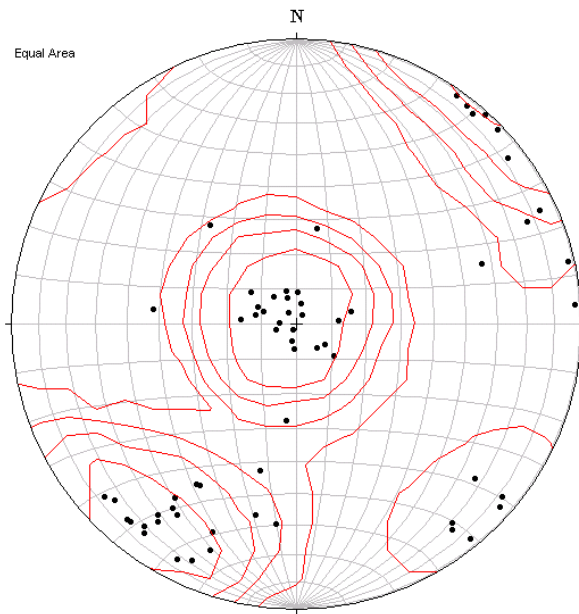


Figure 31. Kamb contour plot of fractures measured at outcrop “wf0447” in the Nashoba Formation (n=63).

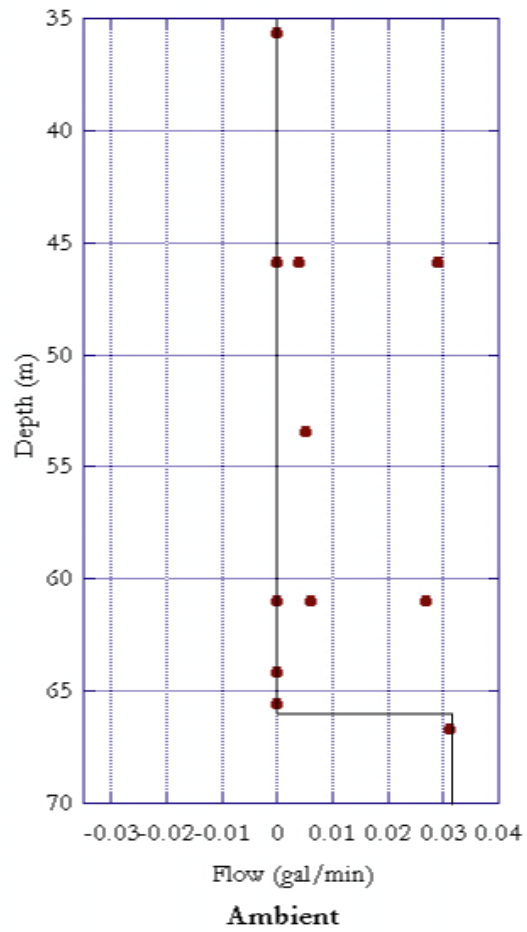


Figure 32. Plot of borehole flow profile from act3.110707. Data collected using Heat Pulse flowmeter.

1.9.3 Regency at Bolton Bolton, MA

The “Regency at Bolton” is a condominium complex that was under construction in 2007. It is located on Rte 117 in Bolton, MA. A pump and storage system was designed for the complex, which includes three bedrock wells. The wells were all drilled within 15 meters of each other on a hill above the complex at 139 meters above sea level. There is a perennial stream and a swamp on the west side of the hill. The three wells all yielded five gallons per minute during pumping tests conducted by the driller. One well in the suite was studied here (bol3.053007). The well was logged from May 25 through May 30, 2007.

There is approximately 11.6 meters of overburden. The overburden material is glacial till composed of a nonsorted, nonstratified matrix of sand with some clay, silt and boulders (Figure 33). The bedrock is the Nashoba Formation. The Nashoba is a fine to medium grained, and well foliated, gray to silvery-gray quartz-mica schist that may contain biotite, garnet and sillimanite (Figure 34).

The total well depth is approximately 97 meters and has a casing length of 15 meters. A total of 36 fractures were identified in the well. The frequency of fractures in the well decreases significantly with depth (figure 35). Of the 36 fractures identified 21 are FPF, ten are tectonic joints, and five are subhorizontal unloading joints. Like many wells in the Nashoba Formation there are two primary fracture sets: the northeast trending FPF, and a set of subhorizontal unloading joints (Figure 36). Fracture measurements from a nearby outcrop reveal two sets a north-northeast trending set and a west-northwest trending set (Figure 37).

The water table in the well was at 7.35 meters depth. HPFM was conducted under both ambient and pumping conditions. The well was pumped for 1 hour 53 minutes and there was nominal drawdown over that period. Four fractures in the bol3.053007 well were identified as flowing fractures during the HPFM test which is 11% of the total. The fractures were identified at 18.5 (176°, 68°), 41.8 (365°, 0°), 55.0 (210°, 81°), and 61.0 (63°, 14°) meters depth (Figure 38). Of these, one was FPF, one was tectonic and two were subhorizontal unloading joints.

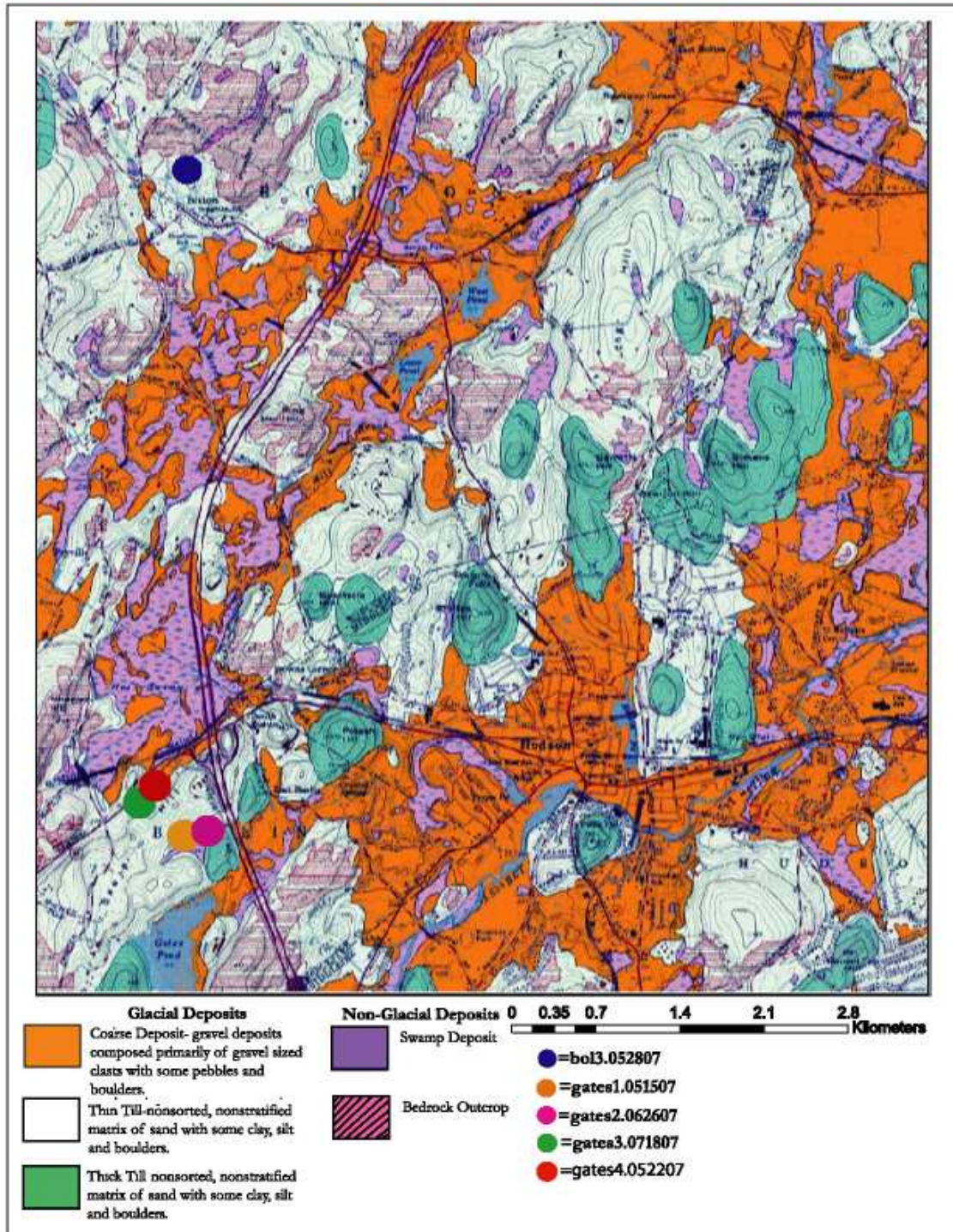


Figure 33. Surficial map of the Bolton, MA-Berlin, MA area derived from the Hudson Quadrangle, Massachusetts (Stone and Stone, 2006).

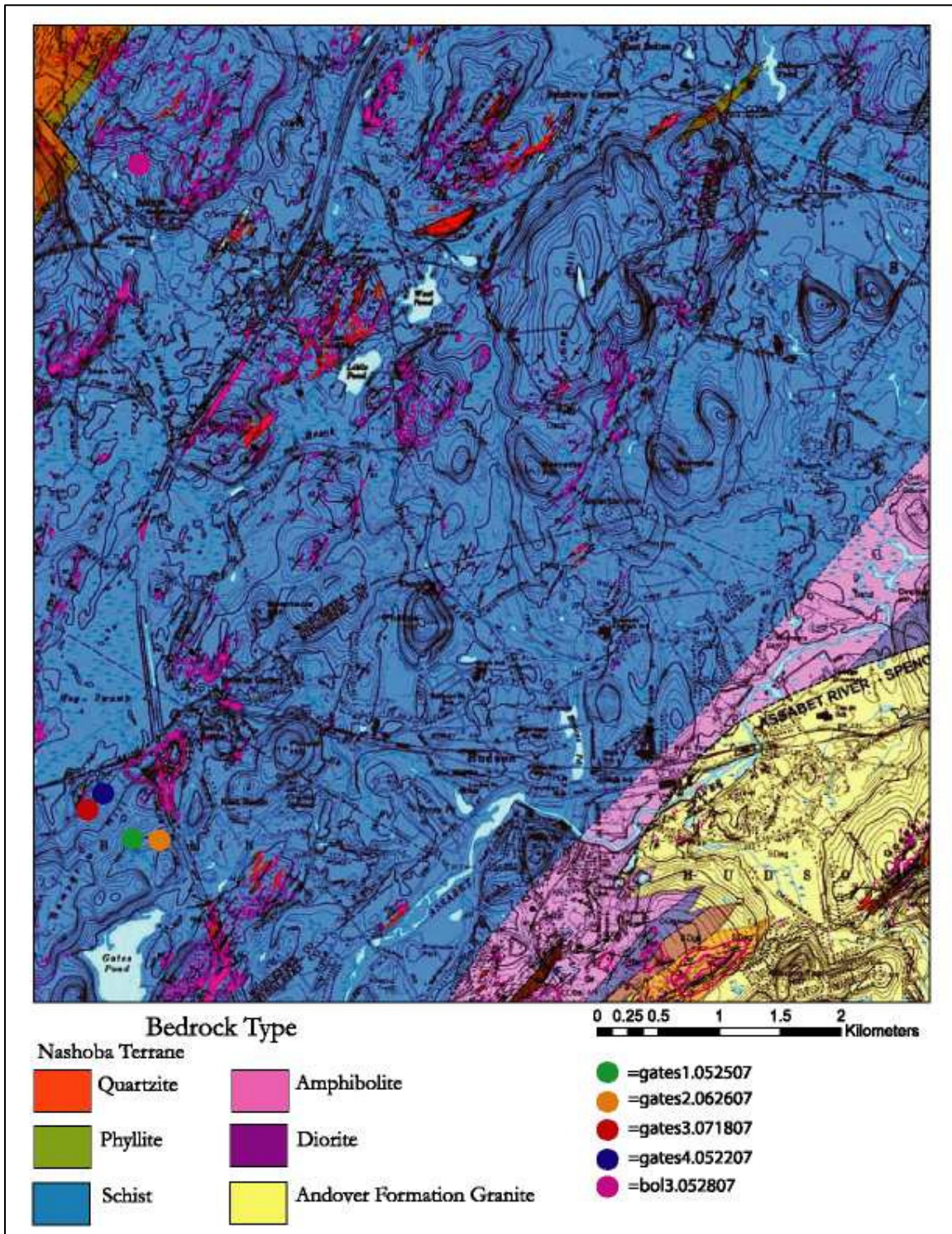


Figure 34. Bedrock map of the Bolton, MA-Berlin, MA area derived from the Hudson Bedrock Quadrangle, Massachusetts (Kopera J., 2005).

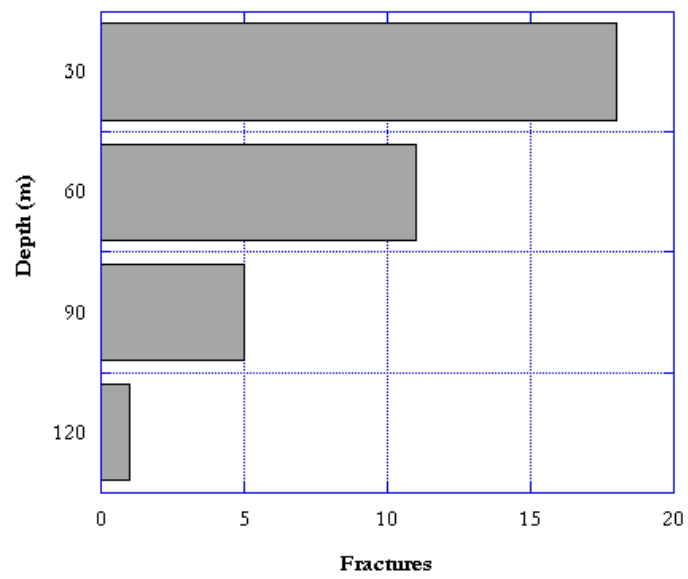


Figure 35. Histogram of fractures versus depth in the bol3.053007 well.

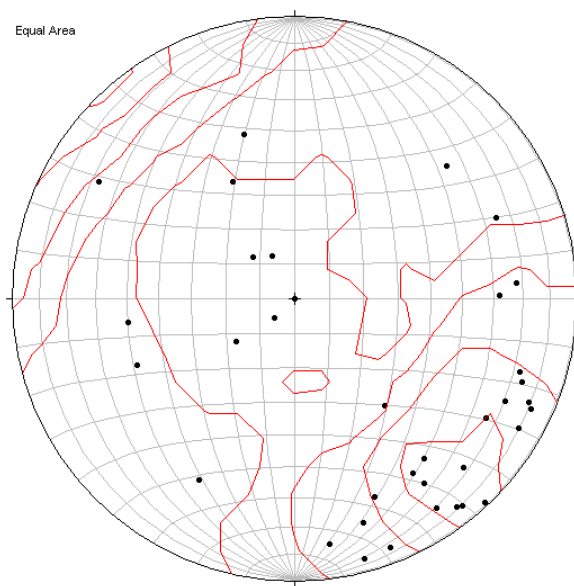


Figure 36. Kamb contour plot of fractures measured in bol3.053007 (n=36).

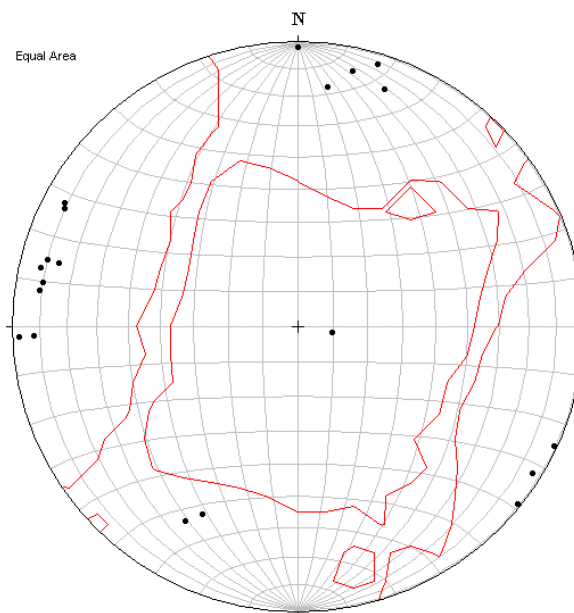


Figure 37. Kamb contour plot of fractures measured at outcrop "hu0147" in the Nashoba Formation (n=20).

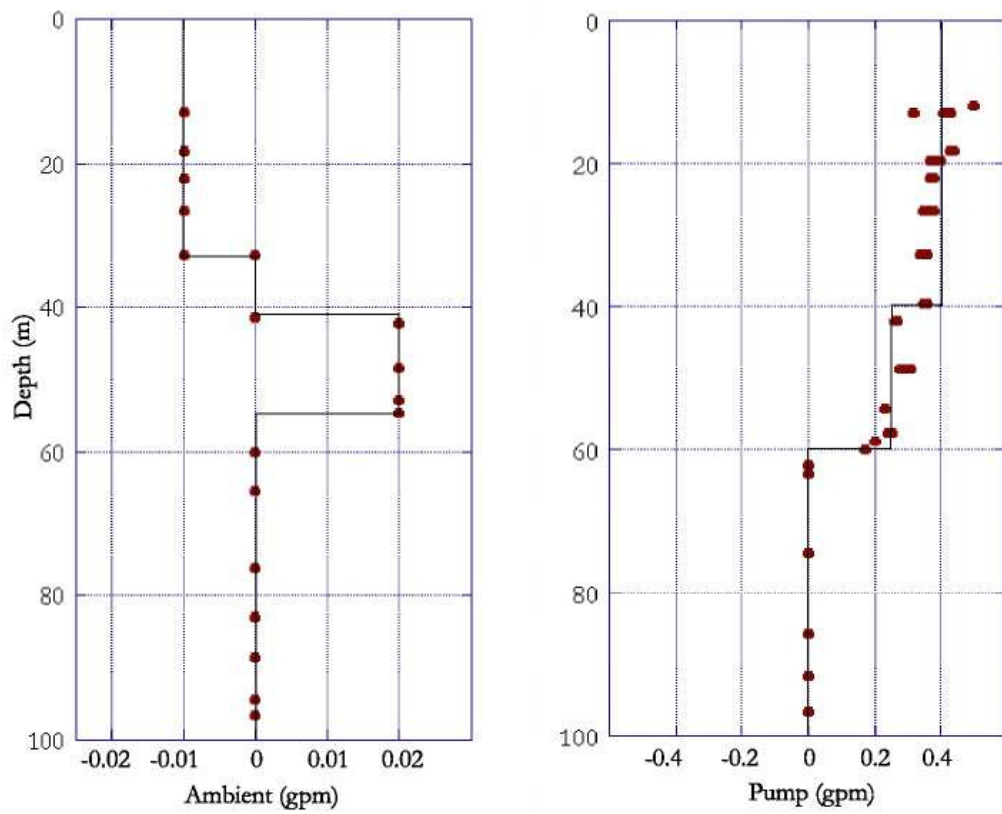


Figure 38. Plot of borehole flow profile from bol3.053007. Data collected using Heat Pulse flowmeter.

1.9.4 Wolf Swamp Boxborough, MA

Wolf Swamp is located off of Burroughs Road in Boxborough, MA. A suite of wells were drilled in a heavily wooded area approximately 200 meters from Wolf Swamp, approximately 93 meters above sea level in the Hudson Quadrangle. They were drilled with the hope of finding a sustainable groundwater source; however the wells did not yield enough for municipal supply and are currently unused. The well, with ID box1.073007, part of this suite of wells and yielded less than gpm in driller tests. The well was logged from July 7 through August 8, 2007.

There is approximately nine meters of glacial till overlying the bedrock. The overburden is nonsorted nonstratified till with a matrix of sand with some clay silt and boulders (Figure 39). The bedrock is Nashoba Formation. The Nashoba is a fine to medium grained, and well foliated, gray to silvery-gray quartz-mica schist that may contain biotite, garnet and sillimanite (Figure 40).

The well is approximately 183 meters deep with 212 fractures over that length. The frequency of fractures with depth is inconsistent with the common trend seen in the field as there is no decrease in frequency with depth (Figure 41a and b). Of the total 42 are subhorizontal unloading joints, 86 are FPF and the remaining 84 are tectonic fractures. There are five major sets in this well: a subhorizontal unloading joint set, an east-northeast trending set, a moderately dipping northwest trending set, a moderately dipping northeast trending set and a north trending set (Figure 42). The number of fractures and the high variability of the orientations are unique. The reasons for this anomaly are not known, however it is possible there is a fault, is affecting the fracture distribution. The fracture sets measured in the well are not consistent with the fractures from a nearby outcrop, where there is a steeply dipping northwest trending set and a northeast trending set (Figure 43).

The water table in the well was at 1.89 meters depth at the outset of the HPFM ambient and pumping tests. For the HPFM pumping test the well was pumped at a ½ gallon per minute for four hours and was drawn down approximately 5 meters over that period. It is clear from this that the yield is as low as reported by the driller. During the tests, two flowing fractures were identified at 20.3 (21°, 46°) and 154.0 (75°, 65°) meters depth (Figure 44). These represent 0.9% of the total fractures identified. One of the flowing fractures is a tectonic joint and the other is an FPF. It is curious that this well has such a high frequency of fractures and yet has such a low yield; however no conclusion can be drawn regarding this anomaly.

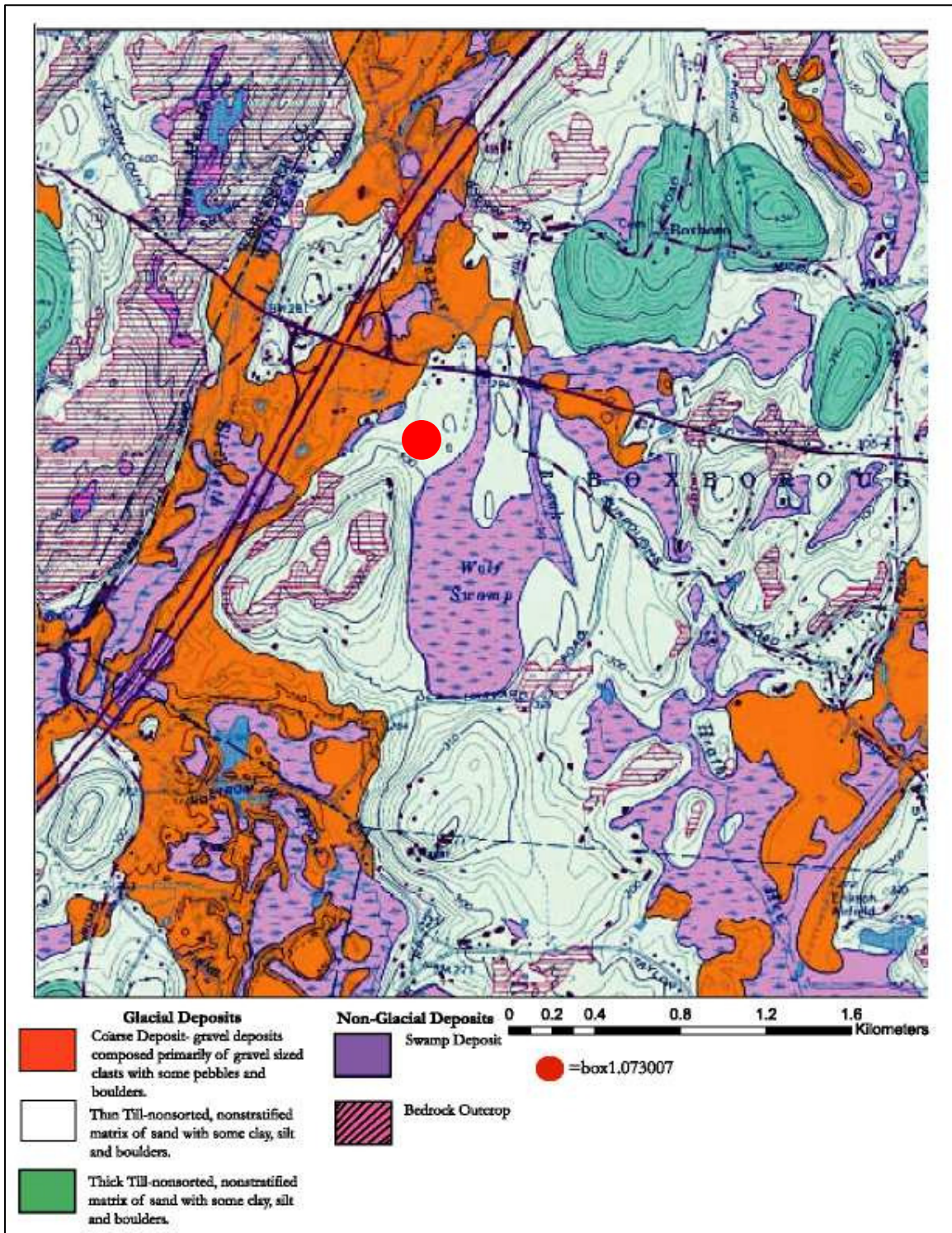


Figure 39. Surficial geologic map of the Boxborough, MA area derived from the Hudson Surficial Geologic Quadrangle, Massachusetts (Stone, 2006).

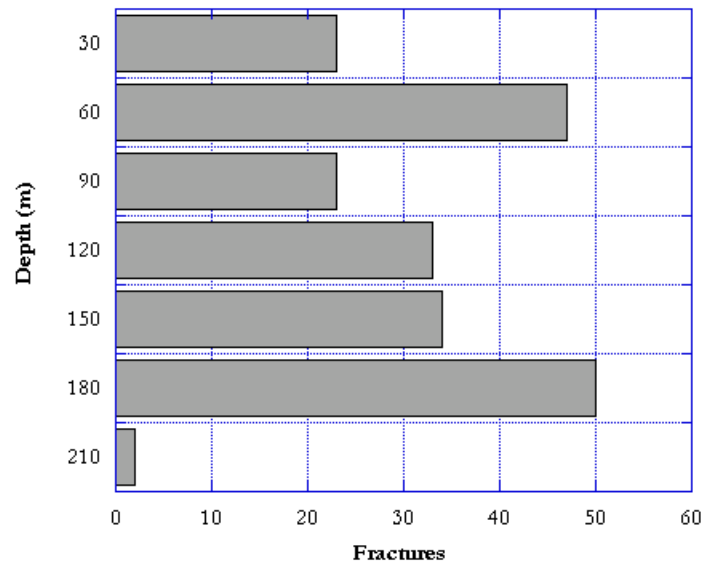


Figure 41. Histogram of fractures versus depth in the bol3.053007 well.

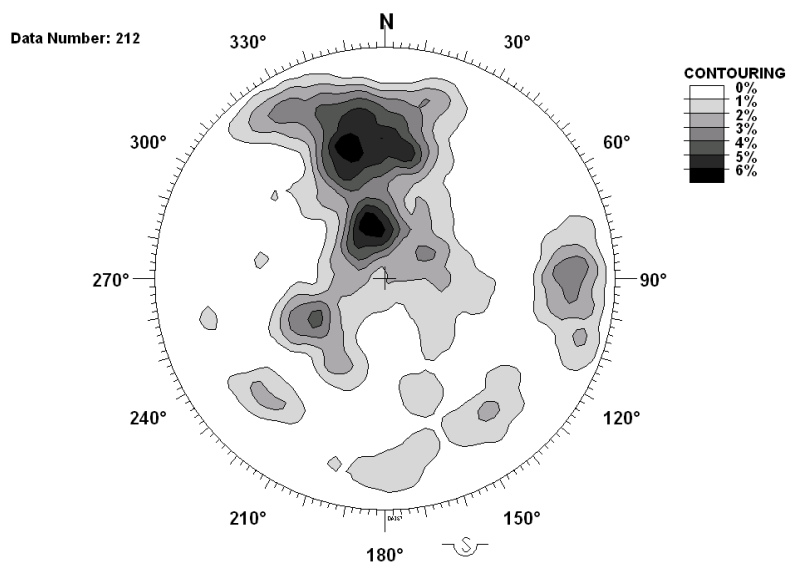


Figure 42a. Stereonet plot of fractures measured in box1.073007 with a 1% contouring interval (n=212).

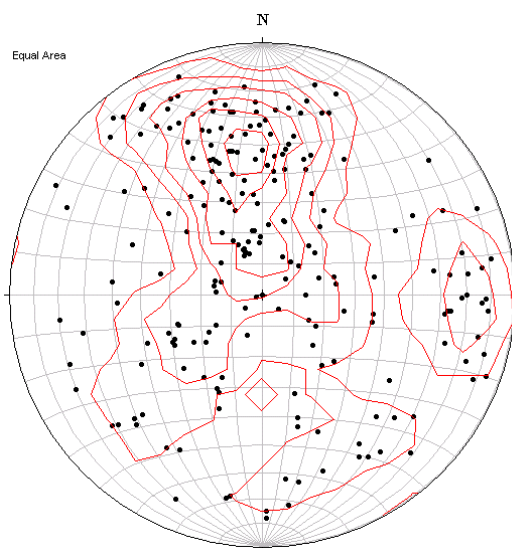


Figure 42b. Kamb contour plot of of fractures measured in box1.073007.

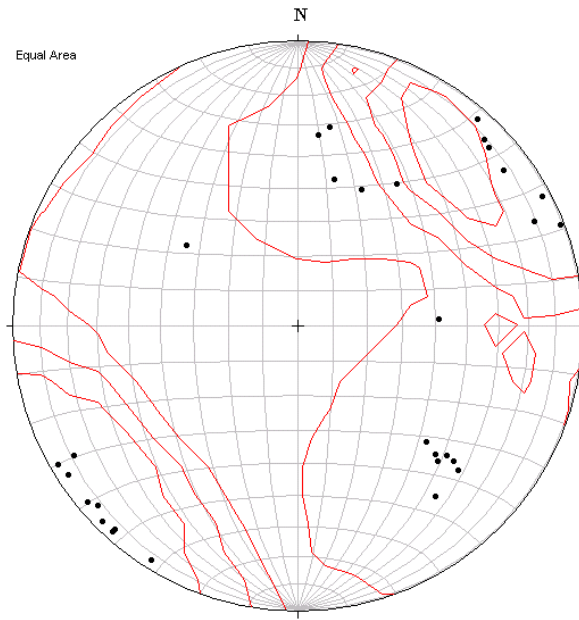


Figure 43. Kamb contour plot of fractures measured at outcrop "ay0464" in the Nashoba (n=30).

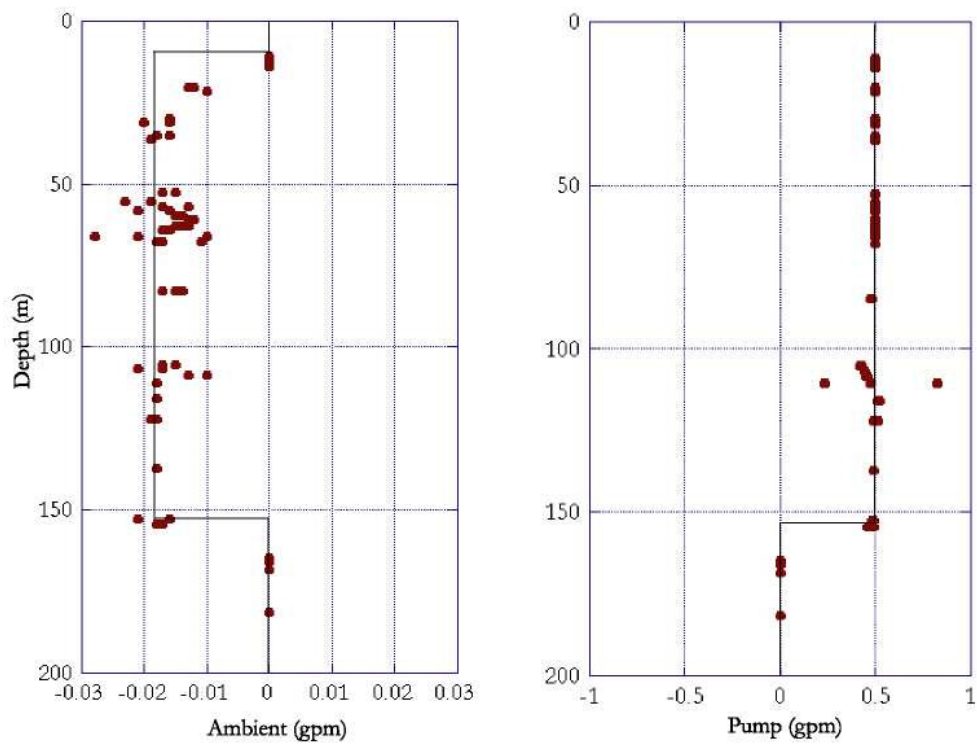


Figure 44. Plot of borehole flow profile from box1.073007. Data collected using Heat Pulse flowmeter.

1.9.5 Gates Pond Berlin, MA

The Gates' Pond Site is located in Berlin, MA along I-495. There are four wells separated by a long elongate outcrop of Nashoba Formation. The wells are approximately 100 meters away from Gates' Pond, which is a surface water supply reservoir for the Town of Hudson, MA. The site is approximately 90 meters above sea level. The town of Hudson commissioned the drilling of the wells in an attempt to find a clean and sustainable groundwater source to replace their surface reservoir. The goal of the project was to drill a suite of groundwater wells which would yield enough water to provide for the entire town. No such source was found so all four wells remain open and unused. The wells were all found to produce five gallons per minute or less in the drillers' pumping test. Three wells were evaluated for this study. They are identified as gates1.051507, gates2.062607 and gates3.071807.

The overburden material at the site is glacial till, of variable thickness, which is composed of a nonsorted, nonstratified matrix of sand with some clay, silt and boulders (Figure 33). The bedrock is Nashoba Formation. The Nashoba is a fine to medium grained, and well foliated, gray to silvery-gray quartz-mica schist that may contain biotite, garnet and sillimanite (Figure 34).

Gates1.051507 Well gates1.051507 was logged from May 15 through 18, 2007 and HPFM tests were run on June 21, 2007. It was reported that the well was 265 meters deep; however it was found to be only 180 meters deep. It is possible that the lower 90 meters collapsed in the year between drilling and logging. The well casing was approximately 7.3 meters in length with about 3 meters of glacial overburden. A total of 255 fractures were identified in this well. Fracture frequency decreases slightly with depth in the well (Figure 45). Of the total fractures 165 are tectonic joints, 26 are subhorizontal unloading joints and 64 are FPF. There were three major fracture sets in this well: an east-west trending set, a northwest trending set, and a north-south striking set (Figure 46a and b). There was also a minor subhorizontal unloading joint set. Two sets were identified at a nearby outcrop of Nashoba formation. Here there was a northeast trending set and a west-northwest trending set (Figure 47).

The water table depth was approximately 1.6 meters at the outset of HPFM pumping. The well was pumped for three hours during which the water level was drawn down 0.07 meters. HPFM tests revealed five flowing fractures, which is 2% of the total; fractures were at 15.7 (187°, 70°), 19.0 (260°, 65°), 21.7 (7°, 55°), 25.0 (331°, 45°), and 73.7 (222°, 21°) meters (Figure 48). Of the flowing fractures two are FPF, two are tectonic joints and one is subhorizontal. The depth and orientation of these fractures is consistent with the developing picture of flow in the Nashoba Formation schist. Flow is generally constricted in to the upper 100 meters and is evenly distributed in fractures of the three fractures types.

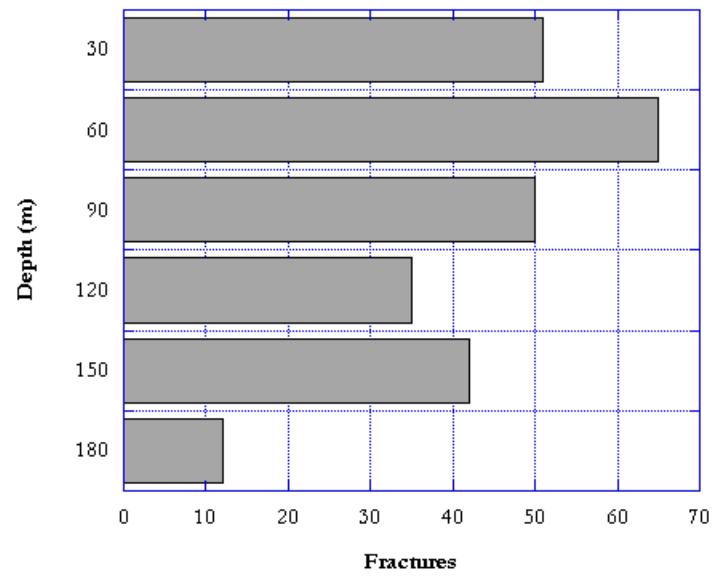


Figure 45. Histogram of fractures versus depth in the gates1.051507 well.

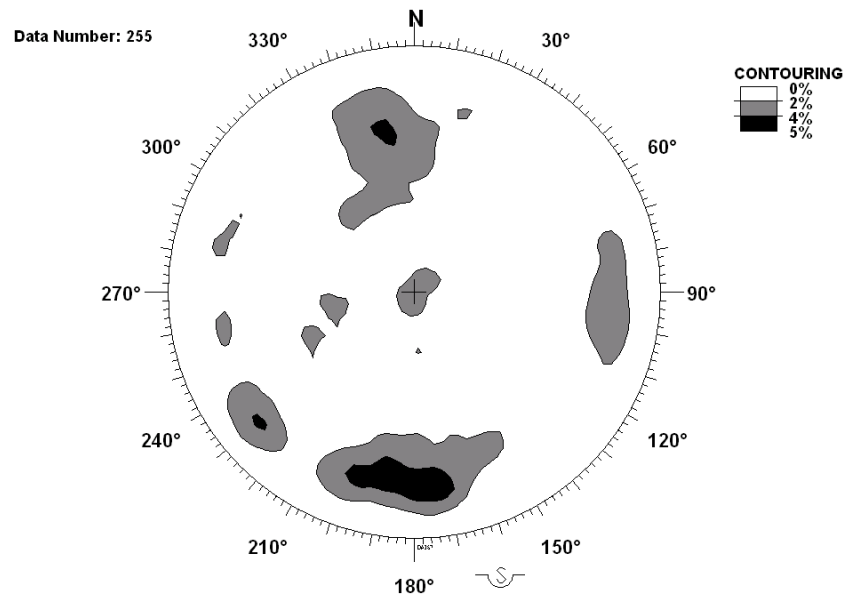


Figure 46a. Stereonet plot of fractures measured in gates1.051507 with a 2% contouring interval.

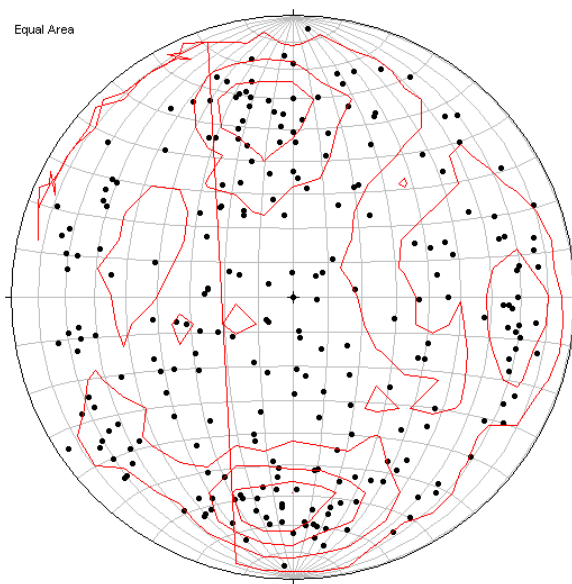


Figure 46b. Kamb contour plot of fractures measured in gates1.051507.

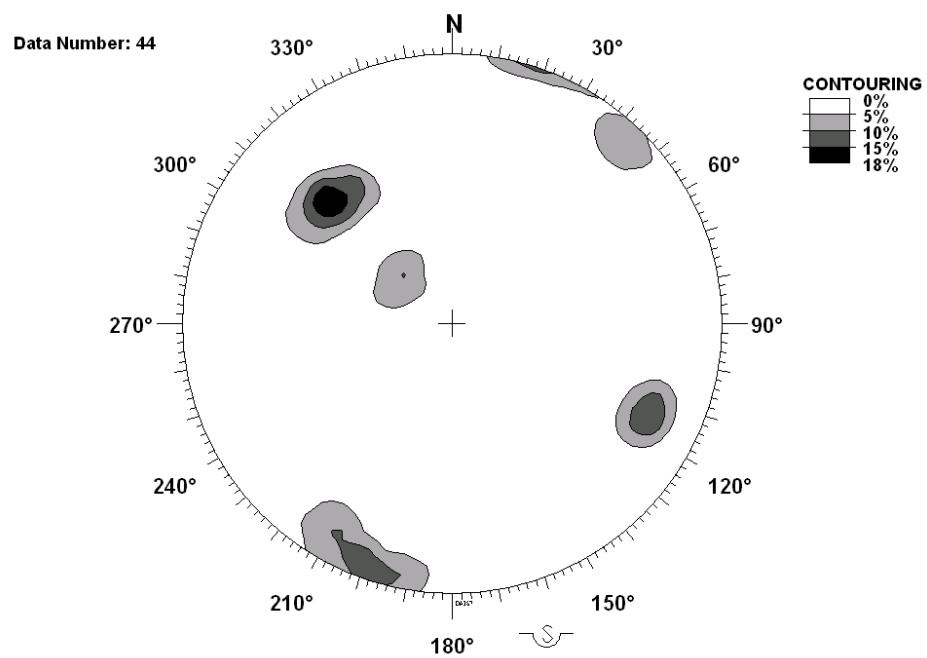


Figure 47. Stereonet plot of fractures measured at outcrop “Hu0371” with a 5% contouring interval.

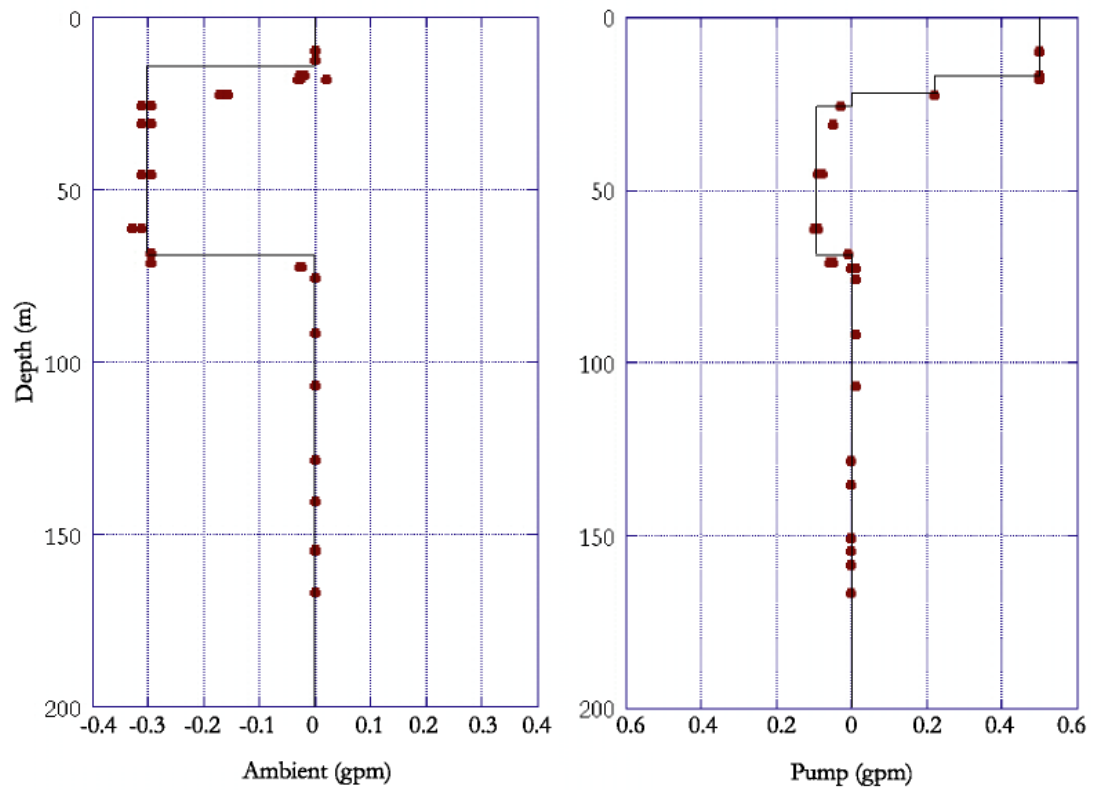


Figure 48. Plot of borehole flow profile from gates1.051507. Data collected using Heat Pulse flowmeter.

Gates2.062607 The gates2.02607 well is approximately 100 meters away from gates1.051507. The well was logged from June 25 through 27, 2007. The well is 242 meters deep with a 6.7 meter long casing. There is approximately two meters of overburden. A total of 187 fractures were identified in the well. The frequency of fractures in the upper 90 meters of the well was significantly higher than below 90 meters (Figure 49). Of the total fractures measured in this well 118 are FPF, 20 are sheeting and 49 are tectonic. There are two prominent fracture orientation sets: the northeast trending FPF set, and a subhorizontal set as seen throughout the Nashoba (Figure 50). In this well, however, the FPF fracture is far more significant than seen in other wells. The trends seen in the subsurface are not entirely consistent with those seen at outcrop (Figure 51). At outcrop scale a significant Northwest trending tectonic set emerges.

The water table in this well was at approximately four meters depth at the beginning of logging. The well was pumped for the HPFM pump test for three hours; during that time the well was drawn down 0.11 meters. Four fractures were identified as flowing fractures which is 2% of the total. Flowing fractures were at 6.95 (289°, 17°), 34.8 (248°, 83°), 69.5 (234°, 60°), and 161.8 (287°, 32°) meters (Figure 52); one flowing fracture was subhorizontal, one was tectonic and two were FPF. The fracture at 6.95 meters, which was measured as a subhorizontal unloading joint, is directly below the base of the casing. This fracture is the dominant flowing fracture, providing 70% of the total borehole flow.

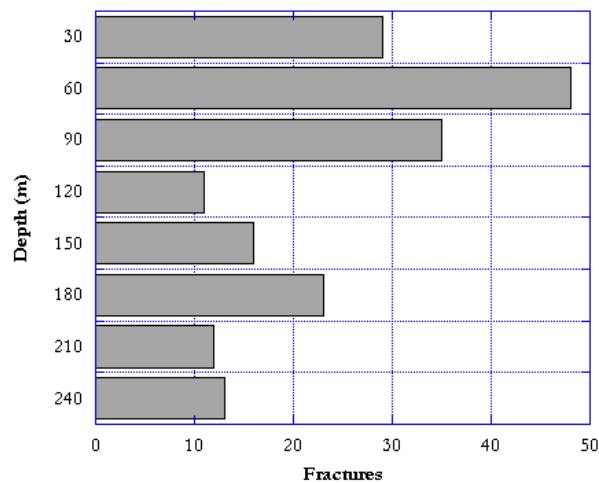


Figure 49. Histogram of fractures versus depth in the gates2.062607 well.

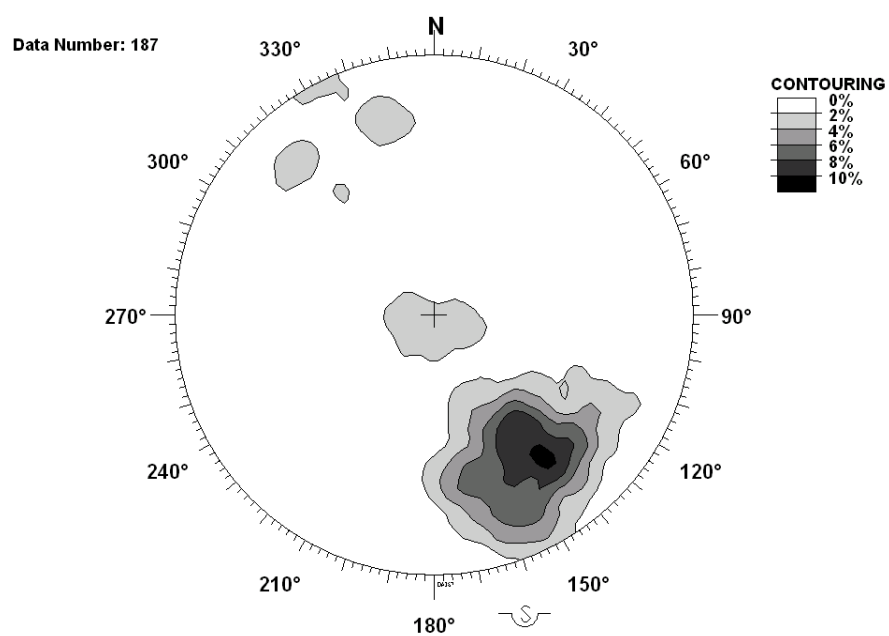


Figure 50a. Stereonet plot of fractures measured in gates2.062607 with a 2% contouring interval.

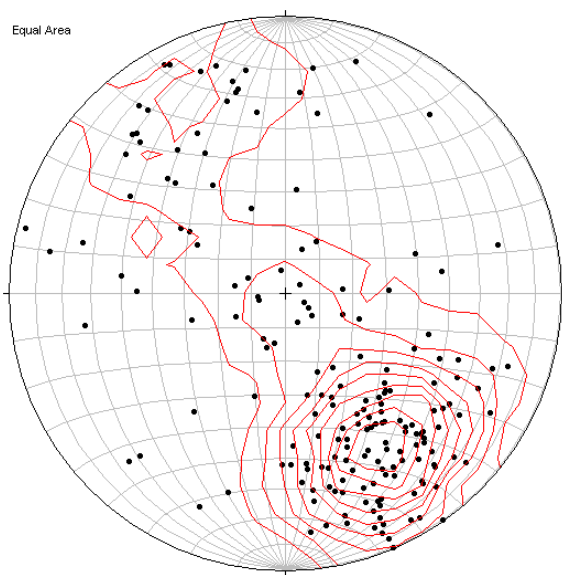


Figure 50b. Kamb contour plot of fractures measured in gates2.062607 (n=187).

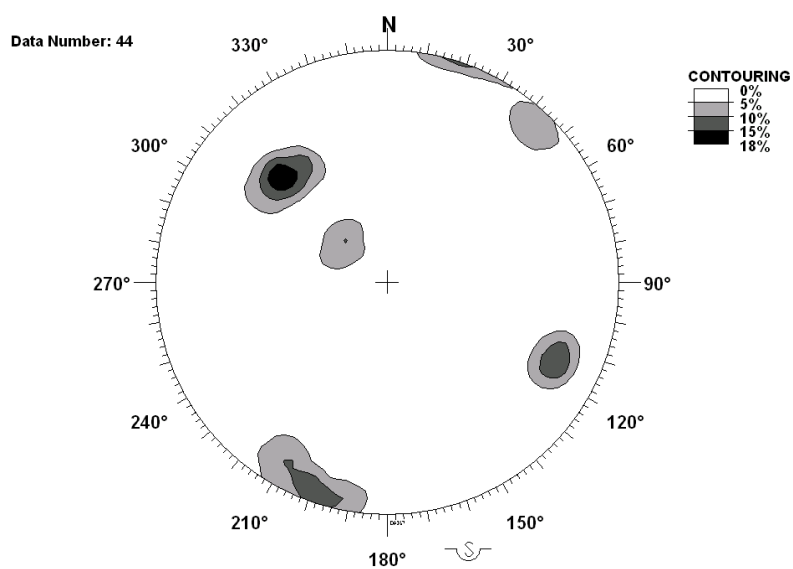


Figure 51a. Stereonet plot of fractures measured at outcrop “Hu0371” with a 5% contouring interval.

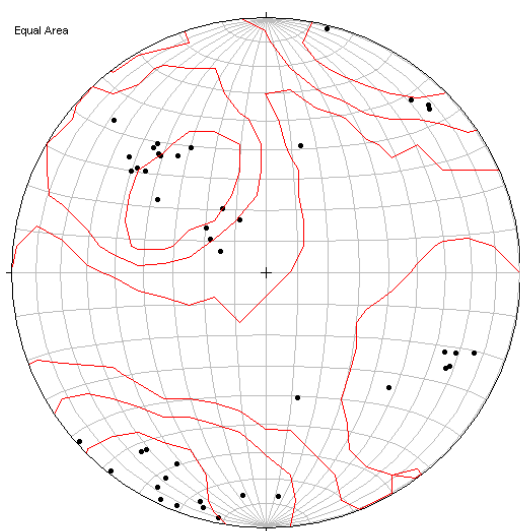


Figure 51b. Kamb contour plot of fractures measured at outcrop “Hu0371” (n=43).

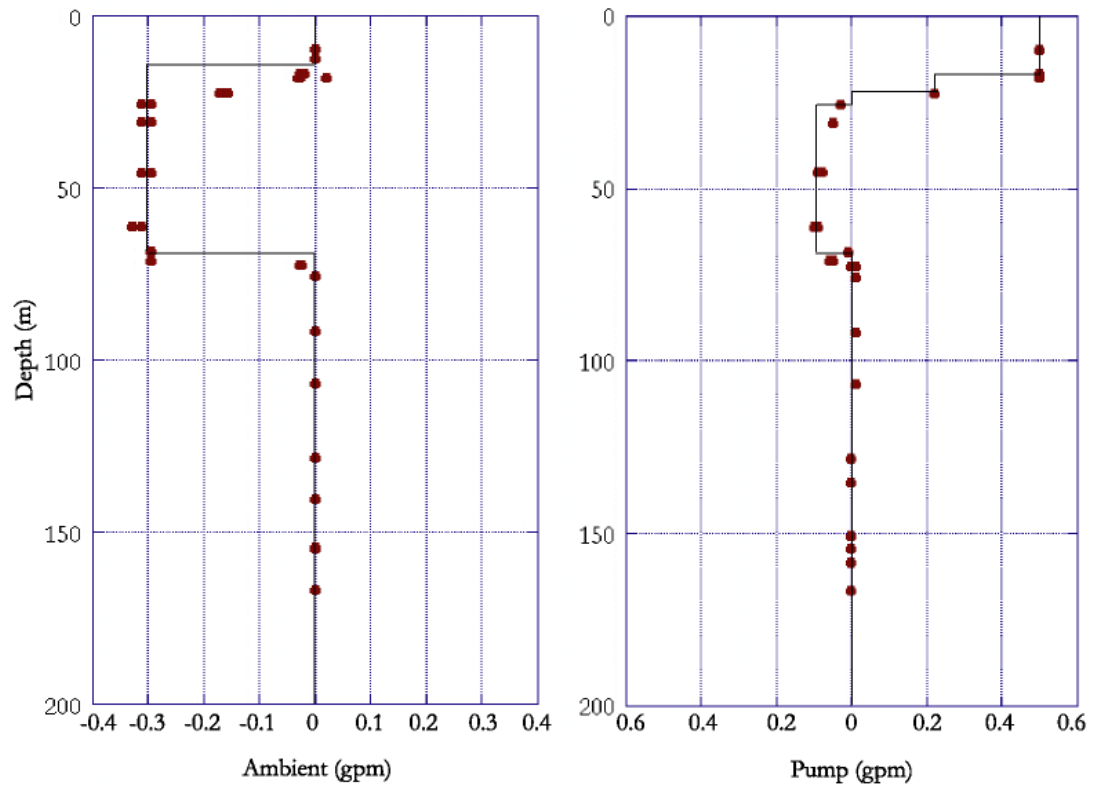


Figure 52. Plot of borehole flow profile from gates2.062607. Data collected using Heat Pulse flowmeter.

Gates3.071807 The well gates3.071807 is approximately 100 meters away from gates1.051507. It is also the closest well to Gates' Pond. Logging in gates3.0718107 began on July 18, 2007 and concluded on May 25, 2008. The well is approximately 243 meters deep with a 6.4 meter casing. There is approximately two meters of overburden. A total of 149 fractures were identified in the well. The frequency of those fractures decreases precipitously with depth, and like gates2.072607, the frequency of fractures decreases suddenly below 90 meters (Figure 53). There are four major fracture sets identified in this well: a large east-west trending set, a north-south trending set, a northeast trending set, and a subhorizontal unloading joint set (Figure 54a and b). There is also a minor northwest trending set present in the well. The nearby outcrop had a northeast trending set, a steeply dipping, west-northwest trending set and a subhorizontal unloading joint set (Figure 55a and b).

The water table was 5 meters below the surface at the outset of pumping for the HPFM tests. The well was pumped for three hours and 16 minutes; during that time the water level was drawn down 0.2 meters. Six fractures were found to be flowing during the HPFM ambient and pumping tests, which is 4% of the total fractures in this well. The fractures were at 13.2 (116°, 74°), 17.5 (190°, 69°), 24.6 (82°, 61°), 40.8 (82°, 55°), 72.2 (221°, 64°), and 92.4 (246°, 6°) meters depth (Figure 56). The depth of the flowing fractures is consistent with the trend seen throughout the Nashoba Terrane; flow is generally constrained to the upper 100 meters of shallow crust. Of all the flowing fractures, one was subhorizontal, one was tectonic and four were FPF. Once again this is generally consistent with the distribution in other nearby wells.

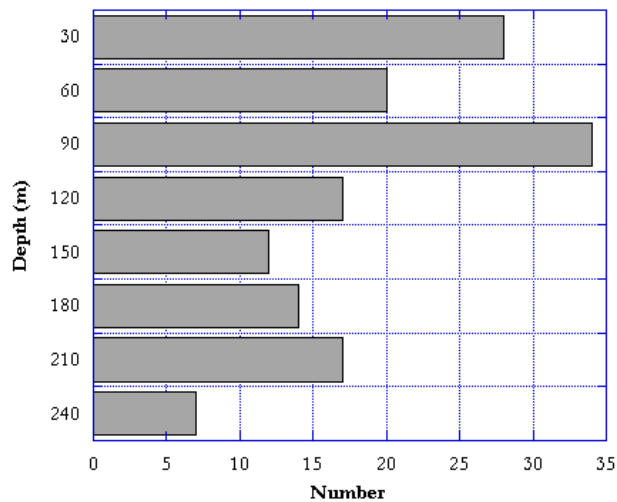


Figure 53. Histogram of fractures versus depth in the gates2.062607 well.

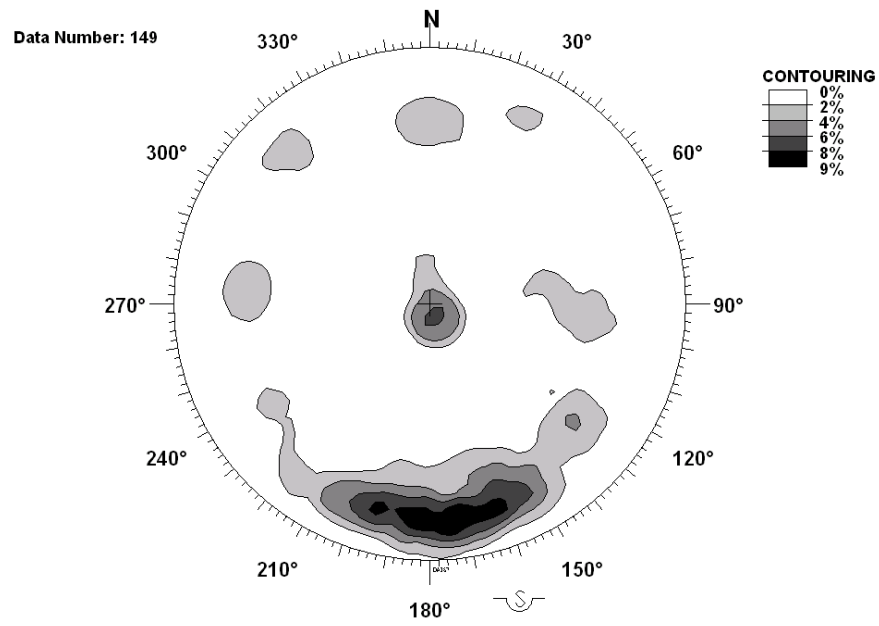


Figure 54a. Stereonet plot of fractures measured in gates3.071807 with a 2% contouring interval.

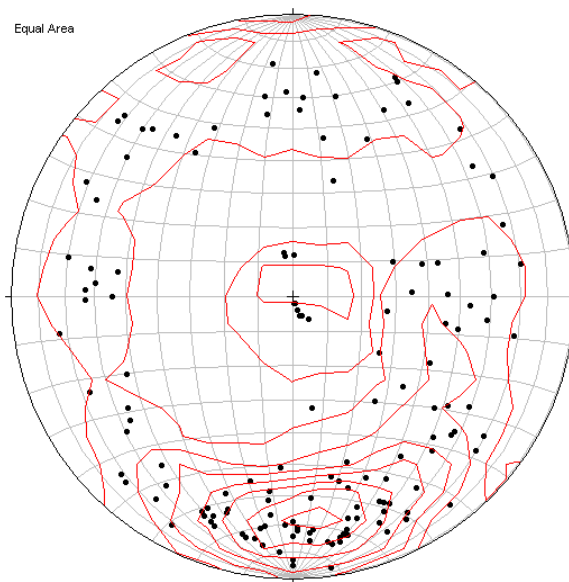


Figure 54b. Kamb contour plot of fractures measured in gates3.071807 (n=149).

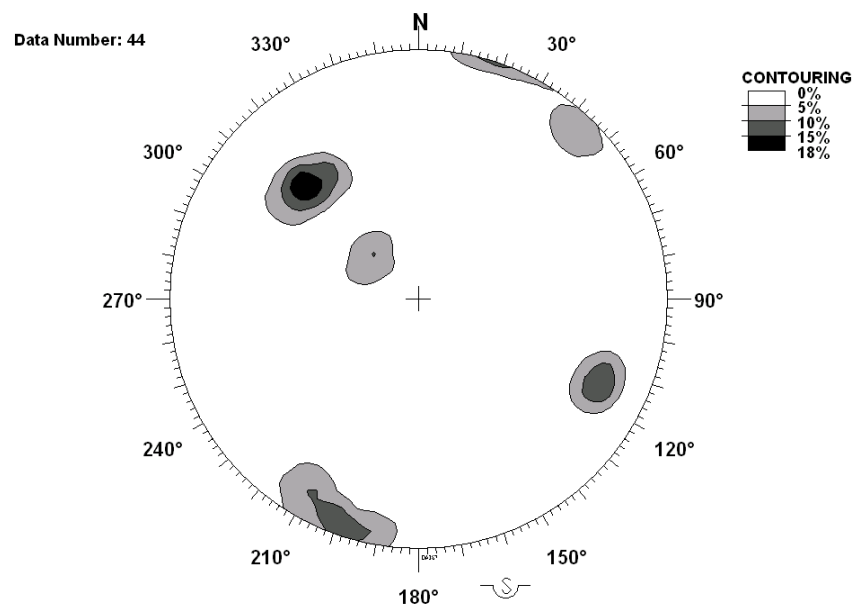


Figure 55a. Stereonet plot of fractures measured at outcrop “Hu0371” with a 5% contouring interval.

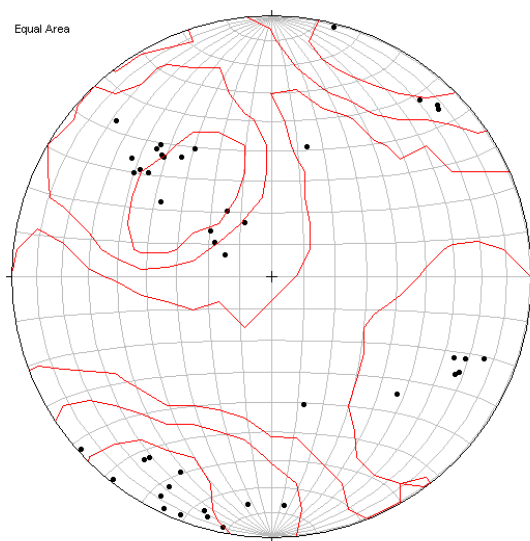


Figure 55b. Kamb contour plot of fractures measured at outcrop “Hu0371” (n=44).

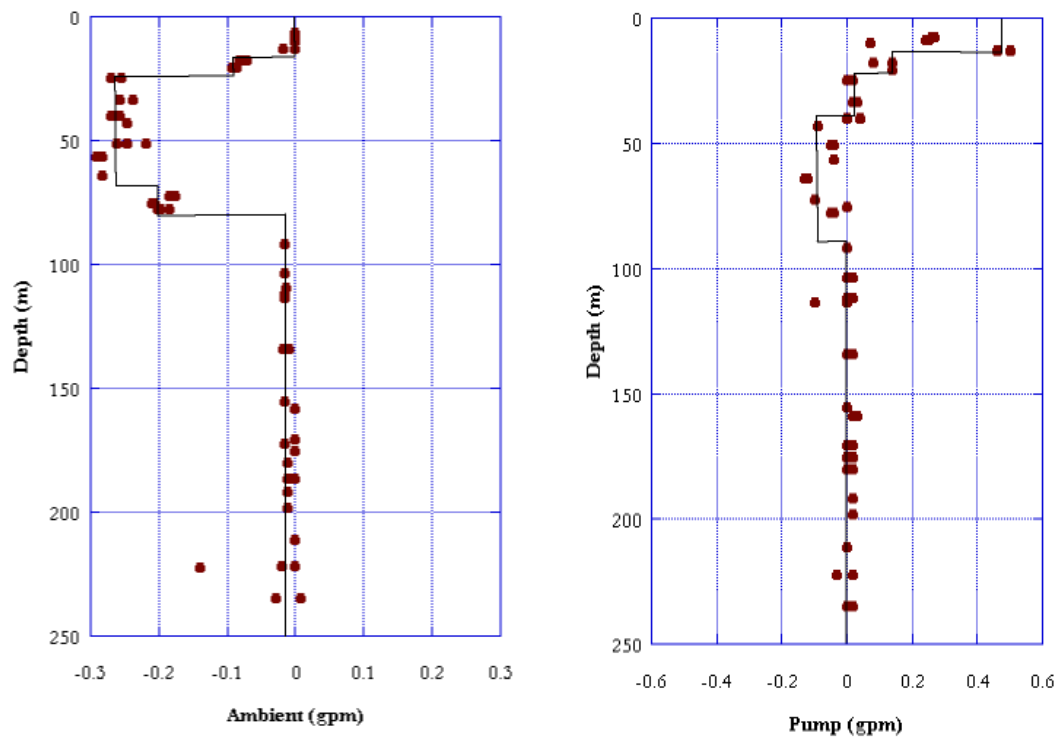


Figure 56. Plot of borehole flow profile from gates2.062607. Data collected using Heat Pulse flowmeter.

1.9.6 Trail Ridge Harvard, MA

“Trail Ridge” is a condominium complex under development off of Ayer Road in Harvard, MA. Trail Ridge sits on the edge of a hill overlooking swampy lowland. Three wells were drilled for a pump and storage system designed for the complex. All three wells had yields estimated at less than five gallons per minute. The well used in this study was estimated at three gallons per minute. The site ID is har1.060407. The well was logged from June 4 through June 7, 2007. The elevation of the site is approximately 130 meters above sea level.

The casing is 5.8 meters in length and the site has approximately 2 meters of glacial till overburden consisting of poorly sorted sand and gravel, with some pebbles and boulders (Figure 57). The well is cased into bedrock, which is the Tadmuck Brook Schist unit. The Tadmuck Brook Schist is sulfidic, quartz-muscovite-biotite schist located along the north-bounding Clinton-Newbury fault zone (Figure 58). There is an outcrop only a few meters from the well, up the hill.

The total depth of har1.060407 is 171 meters. There were a total of 89 fractures identified over the length of the well. The frequency of fractures decreases with depth like wells in other schist formations (Figure 59). At 120 meters there is a sudden increase in fracture frequency. There is no increase in flow at this depth and there are no mapped structural features nearby, thus it is likely that this increase is anomalous. Eight of the total fractures are subhorizontal unloading joints, 56 are tectonic joints and 25 are FPF (approximately 40°, 80°). There are no subhorizontal joints below 40 meters. There are four major fracture sets present in this well: a northeast trending set, a north-south striking set, a northwest trending set and a subhorizontal unloading joint set (Figure 60). There were two sets identified at the nearest outcrop: a moderate to steeply dipping northwest trending set and a moderately dipping northeast trending set (Figure 61).

The water table in the well was 2.9 meters below the ground surface before the onset of the pumping test. The well was pumped at ½ a gallon per minute for four hours drawing the well down 0.3 meters over that time. HPFM tests revealed six flowing fractures over the length of the well which is 10% of the total fractures (Figure 62). The fractures were at 20.2 (34°, 69°), 39.2 (275°, 22°), 43.6 (323°, 39°), 77.3 (41°, 68°), 129 (105°, 53°) and 141.4 (105°, 53°) meters depth. Of the total flowing fractures five are tectonic joints and one is a subhorizontal unloading joint.

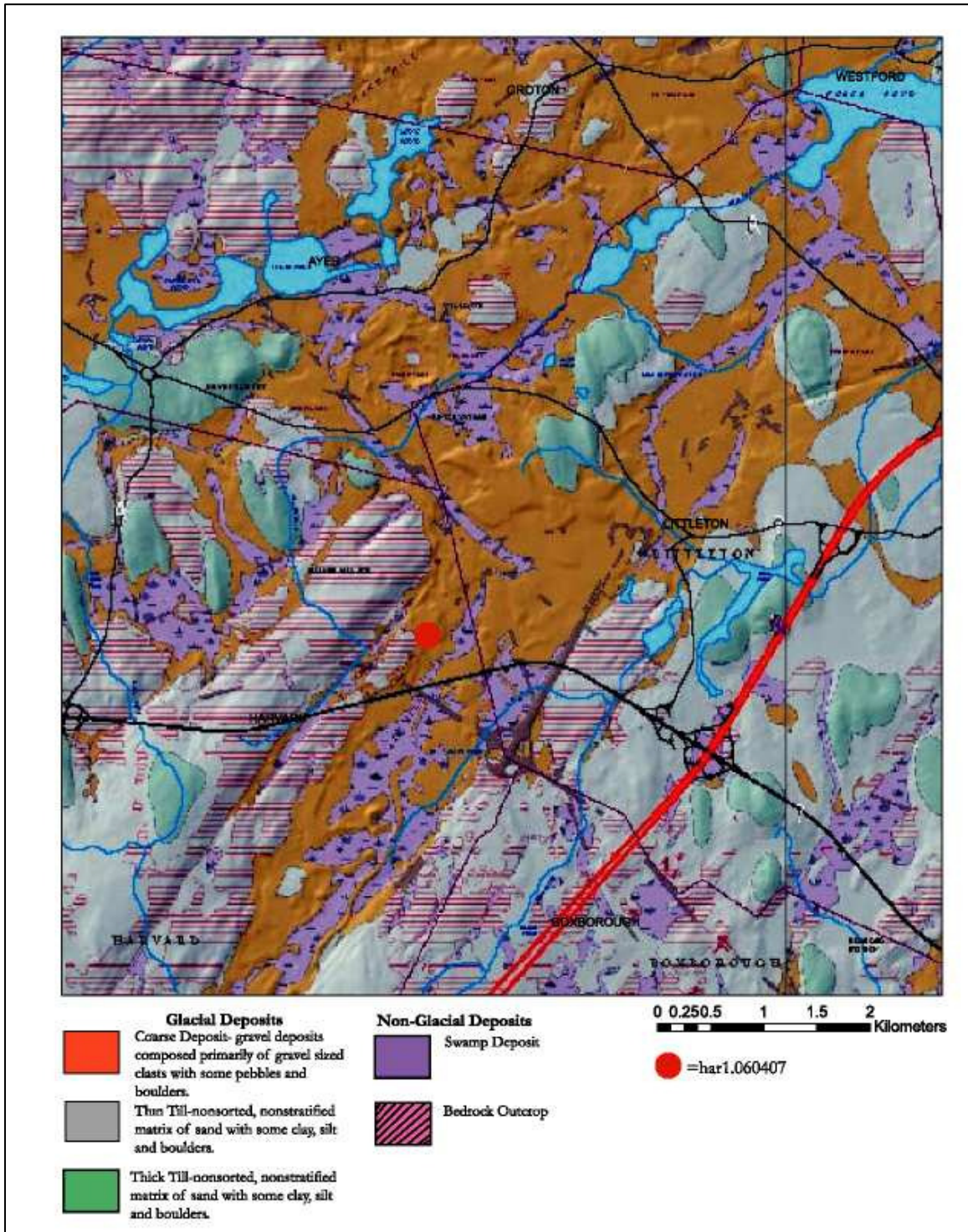


Figure 57. Surficial map of the Harvard, MA area derived from the Ayer Surficial Geological Quadrangle, Massachusetts (Stone and Stone, 2006).

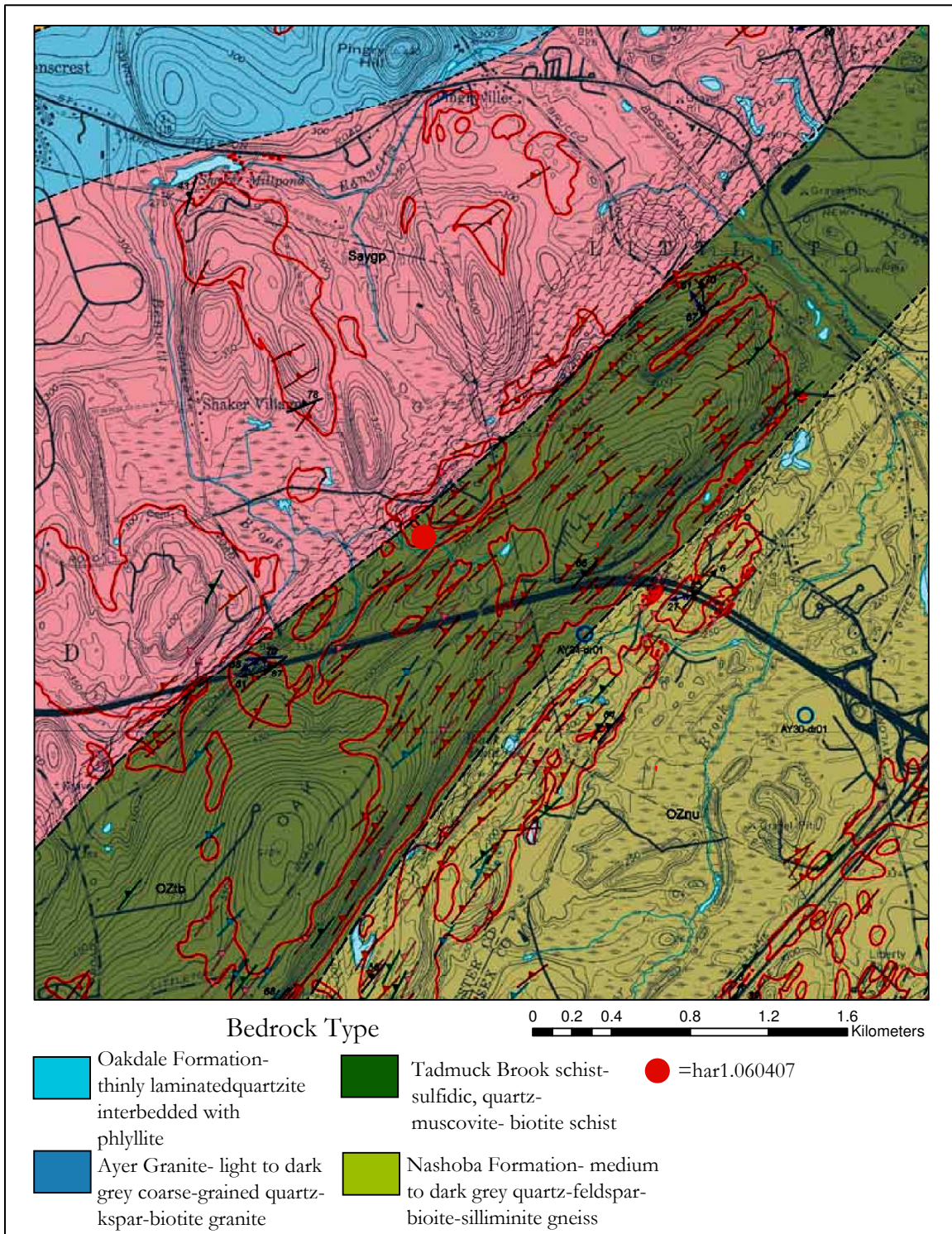


Figure 58. Bedrock map of the Harvard, MA area derived from the Ayer Bedrock Quadrangle, Massachusetts (Kopera, J., 2005).

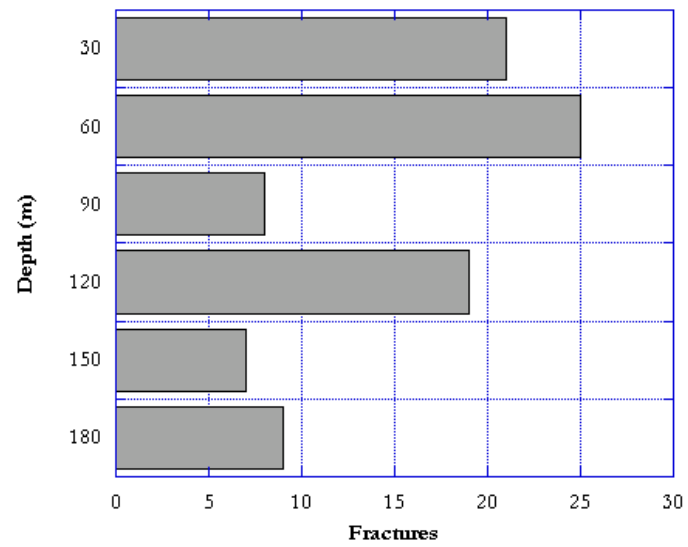


Figure 59. Histogram of fractures versus depth in the har1.060407 well.

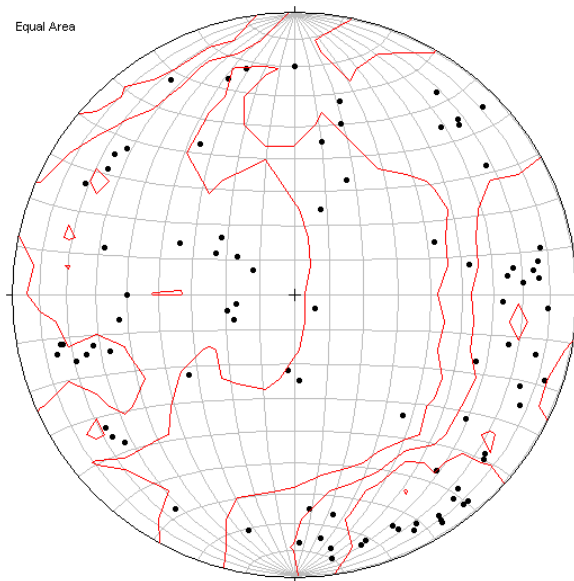


Figure 60. Kamb contour plot of fractures measured in har1.060407 (n=89).

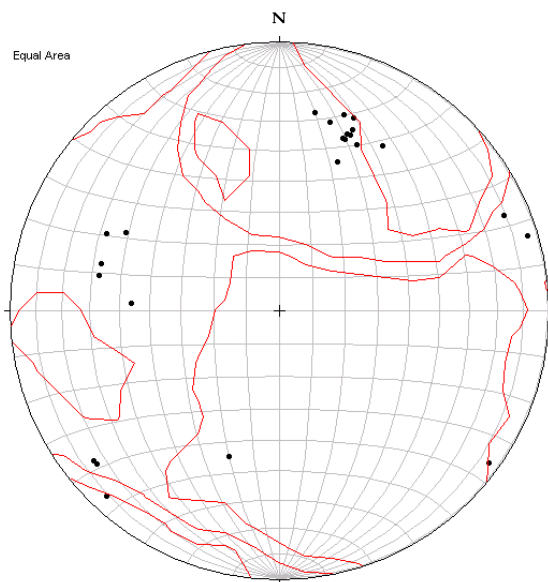


Figure 61. Kamb contour plot of fractures measured at outcrop "ay0463" in the Nashoba Formation (n=23).

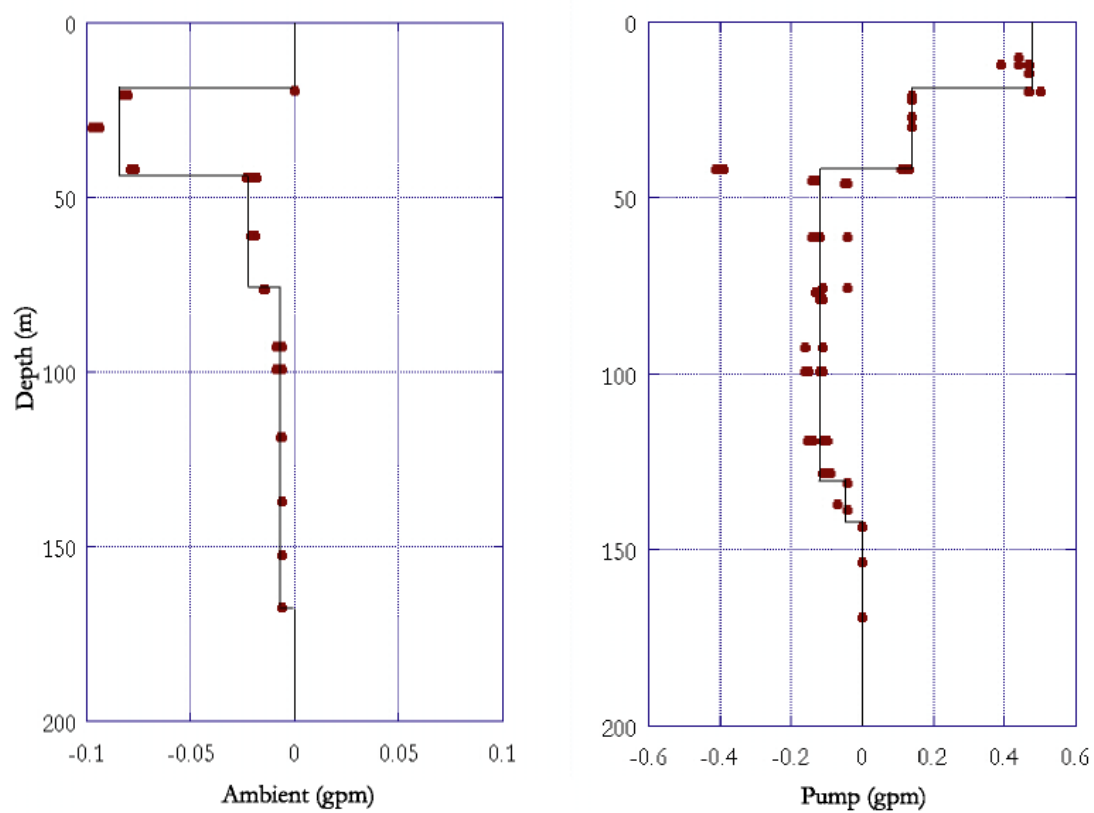


Figure 62. Plot of borehole flow profile from har1.060407. Data collected using Heat Pulse flowmeter.

1.9.7 Maynard PWS Maynard, MA

The town of Maynard, MA commissioned the drilling of a suite of five bedrock wells off of Rockland Ave in 1999. Three of the wells were found to be extremely productive, with yields of well over 100 gallons per minute, and are used as public water supply wells to date. The fourth well yielded 60 gallons per minute and is currently unused; that well was used for this study. A yield of 60 gallons per minute makes this well the most productive in the Nashoba well suite. The well ID is may2.061307 the well is approximately 61 meters above sea level. The well was logged from May 29 through June 13, 2007. The well is in a densely wooded area between a soccer field, a swampy area and the Maynard water treatment facility.

The well is cased through ten meters of surficial overburden. The material is poorly sorted sand gravel with some pebbles and boulders (Figure 63). The bedrock is an unnamed amphibolite-gneiss unit. It is primarily a fine to medium-grained hornblende-actinolite-biotite-quartz-plagioclase orthogneiss with strongly defined lineation. The unit lies between the Nashoba Formation Schist and a large mapped fault in the Nashoba Terrane (USGS open-file report 01-354).

The well is 183 meters deep with 15 meters of casing. A total of 166 fractures were identified over that length. The fracture frequency of this well does not decrease with depth (Figure 64); in fact, the highest fracture frequency in the may2.061307 well is between 120 and 180 meters depth. Of the total fractures measured 64 were FPF, 13 were subhorizontal and 89 were tectonic joints. There were five dominant fracture sets in this well: a northeast set, a north-south striking set, an east-west trending set, a northwest trending set and a subhorizontal unloading joint set (Figure 65a and b). At the nearest outcrop there were two sets identified: a northeast and a northwest striking set (Figure 66).

The water level in the well was 7.6 meters down at the outset of logging. This is seven meters deeper than the water level measured in the well prior to driller pump tests in 1999. It is likely that the water level has dropped seven meters over the nearly ten years of pumping from the aquifer near the may2.061307 well. It is therefore likely that all the wells in the suite are hydrologically connected in the subsurface. By arrangement with the town of Maynard the nearby wells were not pumped during the HPFM tests to ensure accuracy. The well was pumped for three hours seven minutes during which the well was drawn down 0.13 meters. HPFM revealed five flowing fractures at 31.2 (195°, 52°), 48.6 (73°, 74°), 76.5 (217°, 86°), 90.2 (225°, 2°), and 100.7 (176°, 84°) meters depth (Figure 67). Of the flowing fractures one is tectonic, one is subhorizontal and the remaining three are FPF.

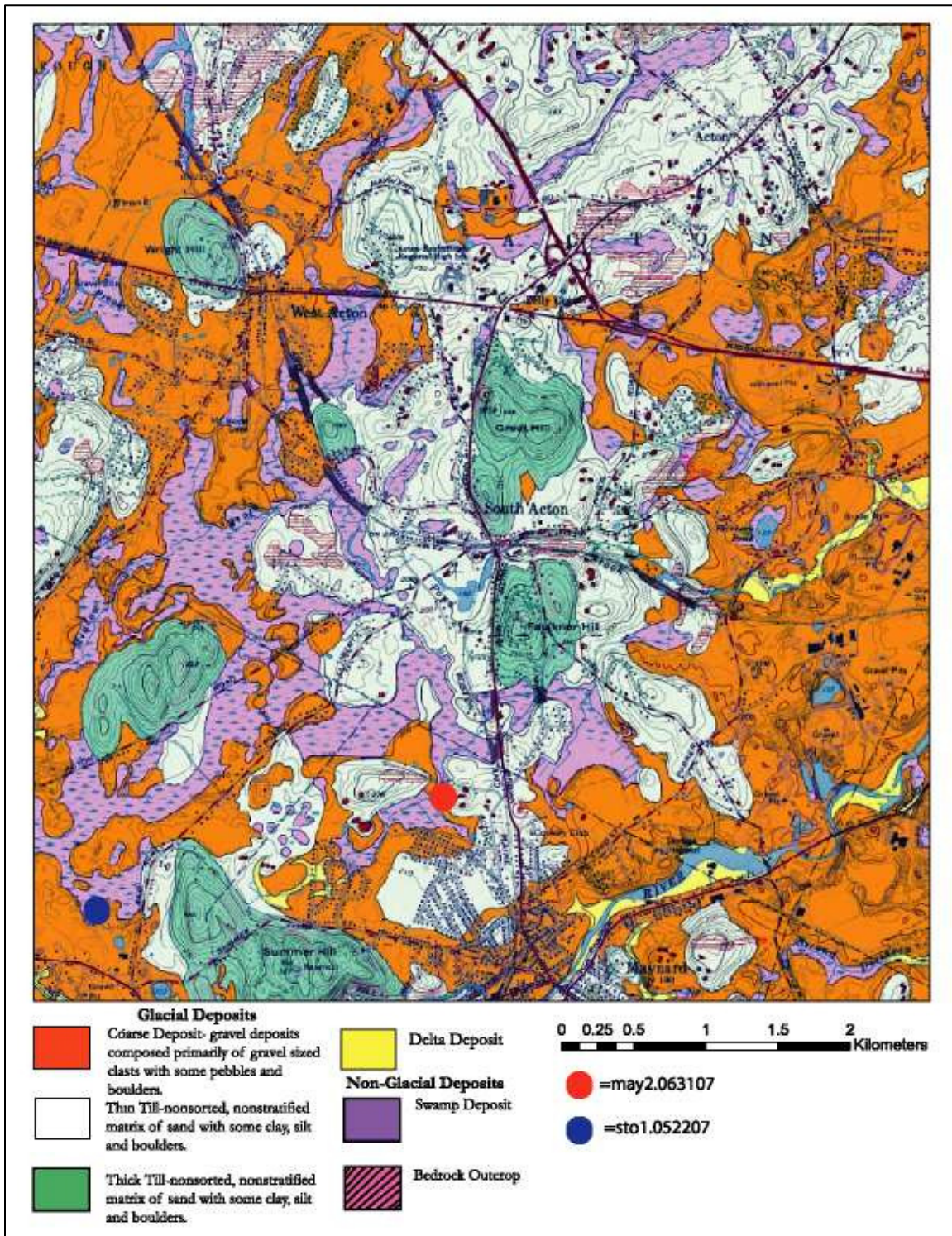


Figure 63. Surficial map of the Maynard, MA and Stow, MA area derived from the Maynard Surficial Geological Quadrangle, Massachusetts (Stone and Stone, 2006).

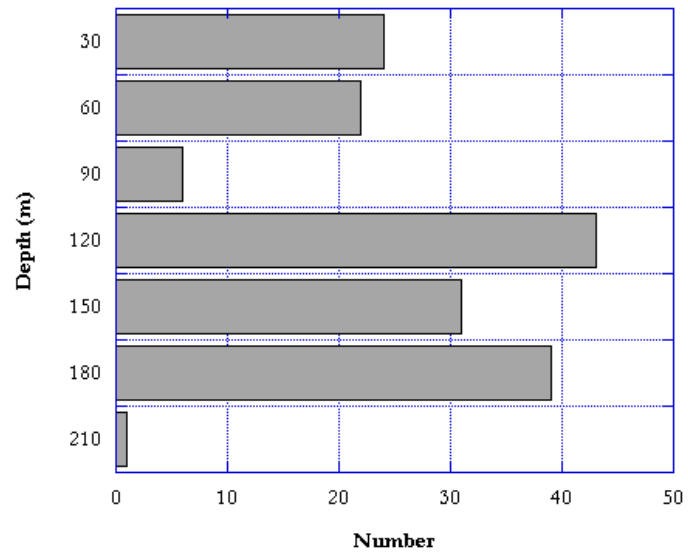


Figure 64. Histogram of fractures versus depth in the may2.061307 well.

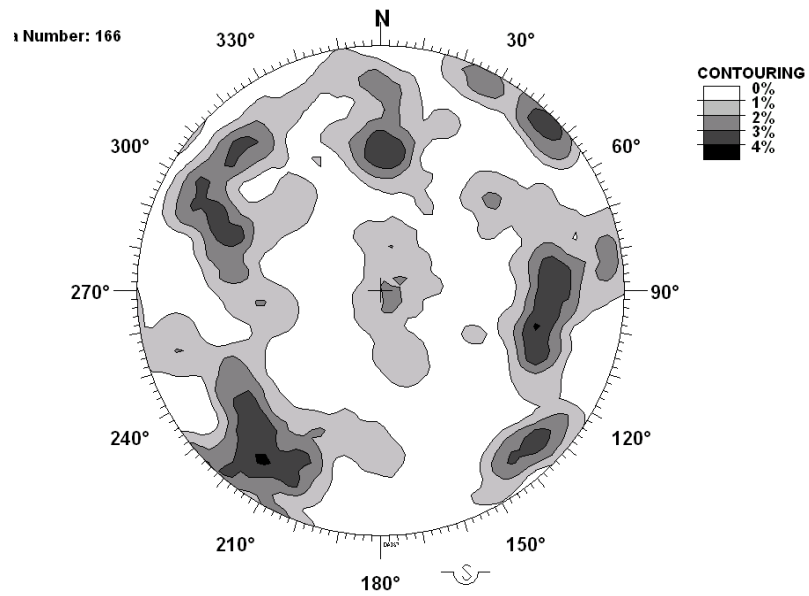


Figure 65a. Stereonet plot of fractures measured in may2.061307 with a 1% contouring interval.

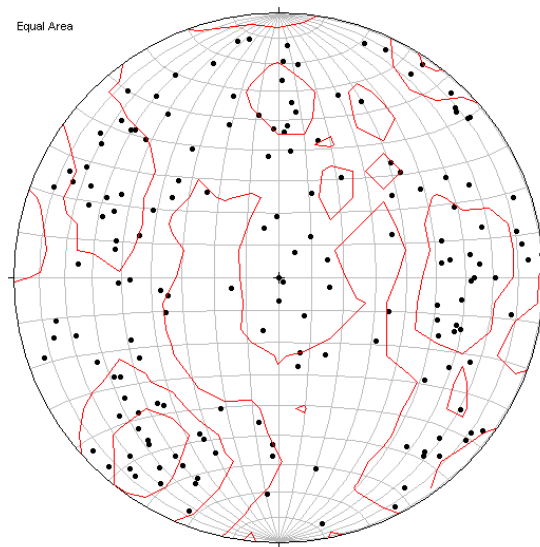


Figure 65b. Kamb contour plot of fractures measured in may2.061307 (n=166).

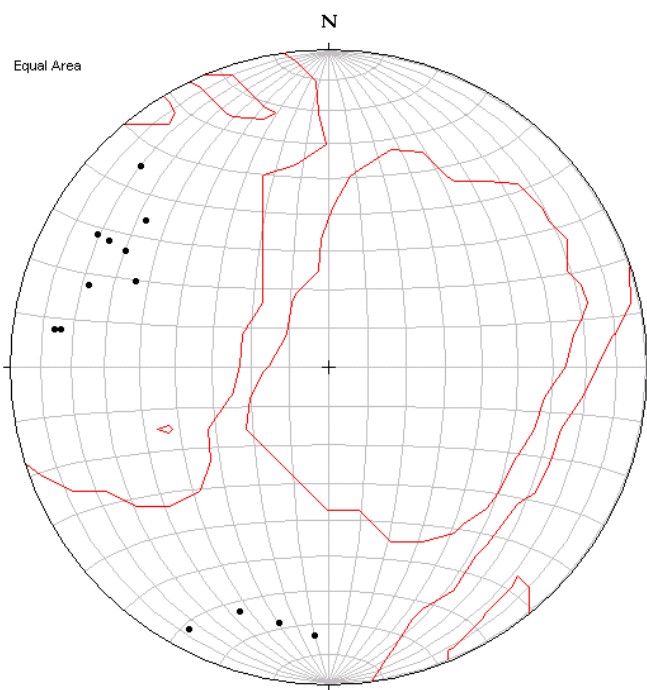


Figure 66. Kamb contour plot of fractures measured at outcrop “ma0277” in the Nashoba Formation (n=13).

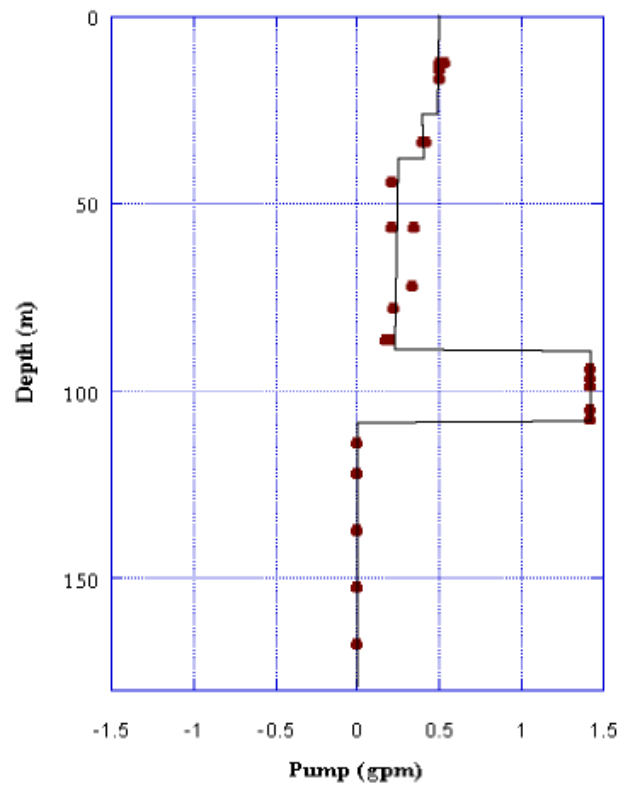
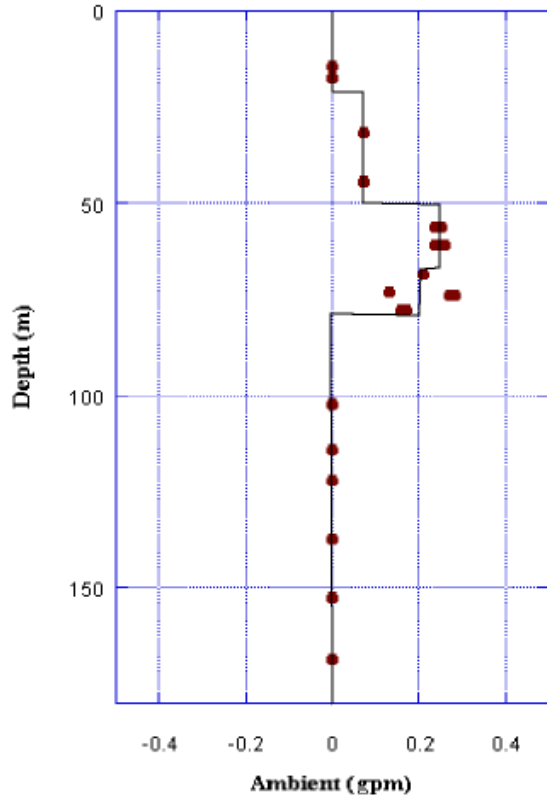


Figure 67. Plot of borehole flow profile from may2.061307. Data collected using Heat Pulse flowmeter.

1.9.8 I-495 Interchange Marlborough, MA

During highway construction the Massachusetts Highway Department (MHD) commissioned a well which was drilled in the middle of a highway interchange. The well is open and unused to date. This 33 meter deep well was logged on June 25, 2007 and was completed in one day. The ID is nor1.062507. The well code “nor” refers to Northborough, MA. The elevation of the well is approximately 138 meters above sea level. There is a large outcrop of bedrock 10 meters away, which was blasted out during highway construction.

The top of the well is at the ground surface and there are only a few centimeters of surficial material on top of the bedrock. The well is located on the margin of the Nashoba Formation and an unnamed amphibolite unit. The bedrock at the location of the well is mapped as an interlayered coarse-grained amphibolite and schist (Figure 68).

Over the length of the 33 meters there were 42 fractures measured. The frequency of fractures does not show any decrease with depth, however the well is so shallow that is unlikely that any trend would emerge (Figure 69). Of the fractures 15 are subhorizontal unloading joints, 13 are tectonic joints and 14 are FPF. This is an unusually high percent of subhorizontal fractures. There are three fracture sets identified in the well: a subhorizontal set a shallow northeast striking set, and a moderately dipping east-west striking set (Figure 70). The two fracture sets identified at the nearest outcrop are similar to those seen in the well; however there was no subhorizontal unloading joint set identified (Figure 71).

The nor1.062507 well flows throughout the spring and summer and was flowing when studied. Additionally, the casing in the well is old and rusted so the water flowing out the well is a bright orange color and fluid resistivity of the water was a good deal lower than other wells. The well was pumped for one hour 59 minutes during which the water level fell 1.2 meters in the well. HPFM tests revealed three flowing fractures at 10.3, 14.7, and 26.6 meters depth (Figure 72). One was FPF, one was tectonic and one was subhorizontal. This is consistent with the distribution of flowing fracture types seen elsewhere. Generally, the distribution of flowing fracture types mirrors the physical distribution.

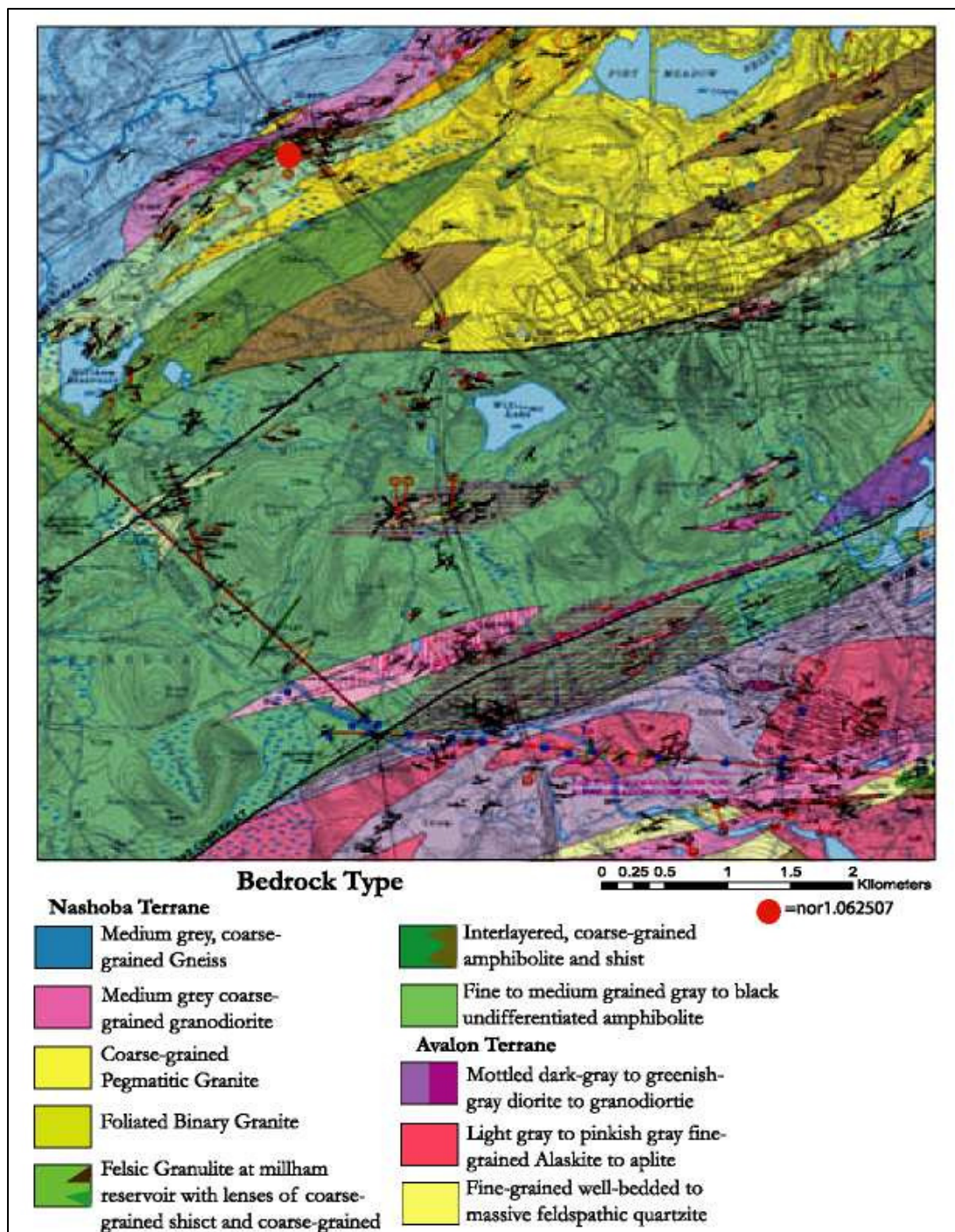


Figure 68. Bedrock map of the Marlborough, MA area derived from the Marlborough Bedrock Quadrangle, Massachusetts (Kopera et al., 2006).

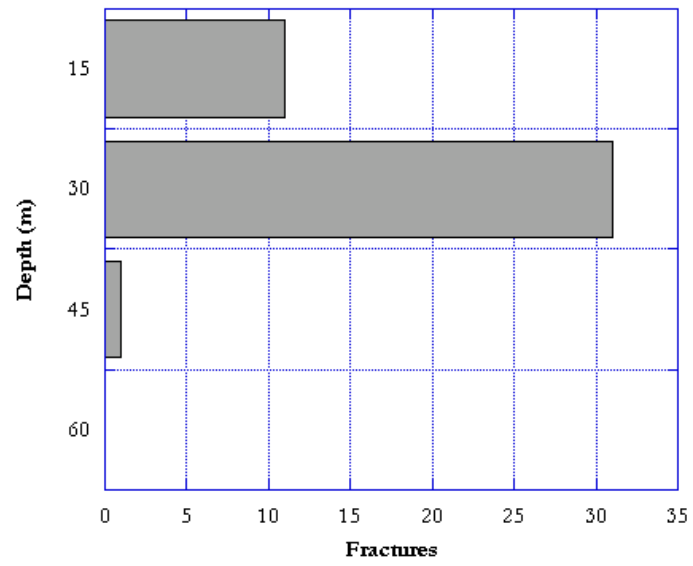


Figure 69. Histogram of fractures versus depth in the nor1.062507 well.

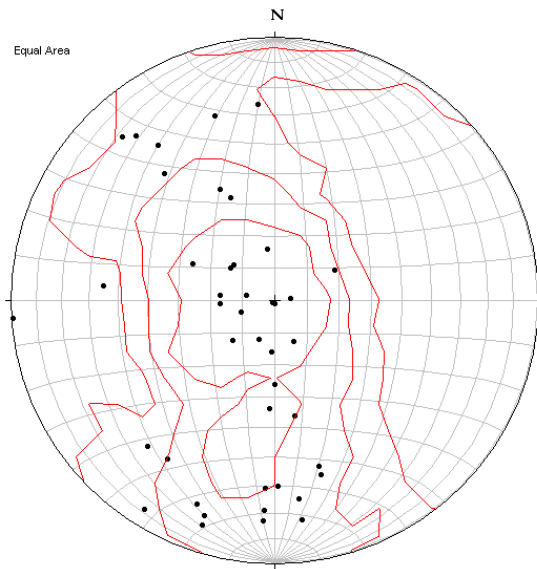


Figure 70. Kamb contour plot of fractures measured in nor1.062507 (n=42).

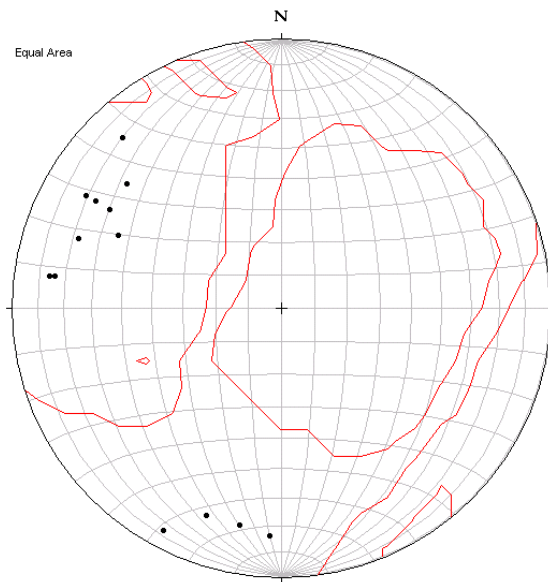


Figure 71. Kamb contour plot of fractures measured at outcrop "ma0277" in the Nashoba Formation (n=13).

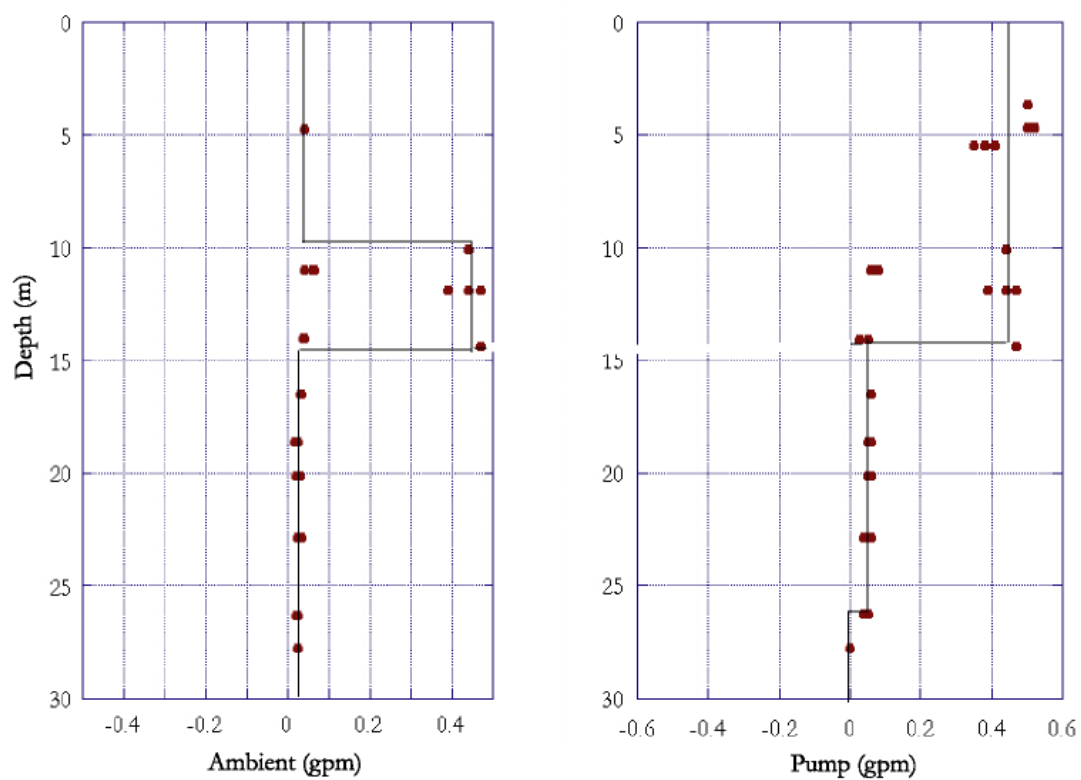


Figure 72. Plot of borehole flow profile from nor1.062507. Data collected using Heat Pulse flowmeter.

1.9.9 Shrewsbury High School Shrewsbury, MA

After construction of the new high school in 2004, the town of Shrewsbury, MA commissioned the drilling of three bedrock wells around the athletic facilities for use on the grounds. Two wells were drilled for the project. One well yielded 60 gallons per minute while the second yielded only 15 gallons per minute. The wells are not currently in use. The 15 gpm well was logged for this project. The ID is shr1.061807 and the well elevation is approximately 173 meters above sea level. The high school is located at the top of hill with large areas of exposed bedrock to either side. The site is approximately three km from the Assabet Reservoir.

There is approximately eight meters of surficial overburden at the site. The overburden is nonsorted, unstratified till with some clay, silt and boulders (Figure 73). The bedrock is a dark gray to greenish gray medium-grained amphibolite (Figure 74). The well site is also approximately three km from the Clinton-Newbury fault.

The well was approximately 214 meters deep, with 95 fractures measured over that length. The frequency of fractures over that length decreases precipitously, and like several other sites in the Nashoba, there is a significant and sudden decrease below 90 meters (Figure 75). Of the total fractures measured in the well three are subhorizontal unloading joints, 25 are tectonic joints, and 67 are FPF indicating that the unit is strongly foliated. There are three major fracture sets at this site: a northeast striking set, a northwest striking set and a shallow dipping east-west striking set (Figure 76). Fractures measured at a nearby outcrop show the same three fracture sets, as well as a subhorizontal unloading joint set (Figure 77).

The water level in the well at the outset of logging was eight meters. The well was pumped for three hours and 25 minutes during which the well was drawn down 0.23 meters. Results from HPFM tests show four flowing fractures which is 4% of the total fractures identified in the well. The fractures were located at 21.3 (270°, 0°), 24.1 (205°, 70°), 26.6 (44°, 62°) and 60 (207°, 71°) meters depth (Figure 78). Of the flowing fractures one was a subhorizontal joint, one was a tectonic joint and two were FPF.

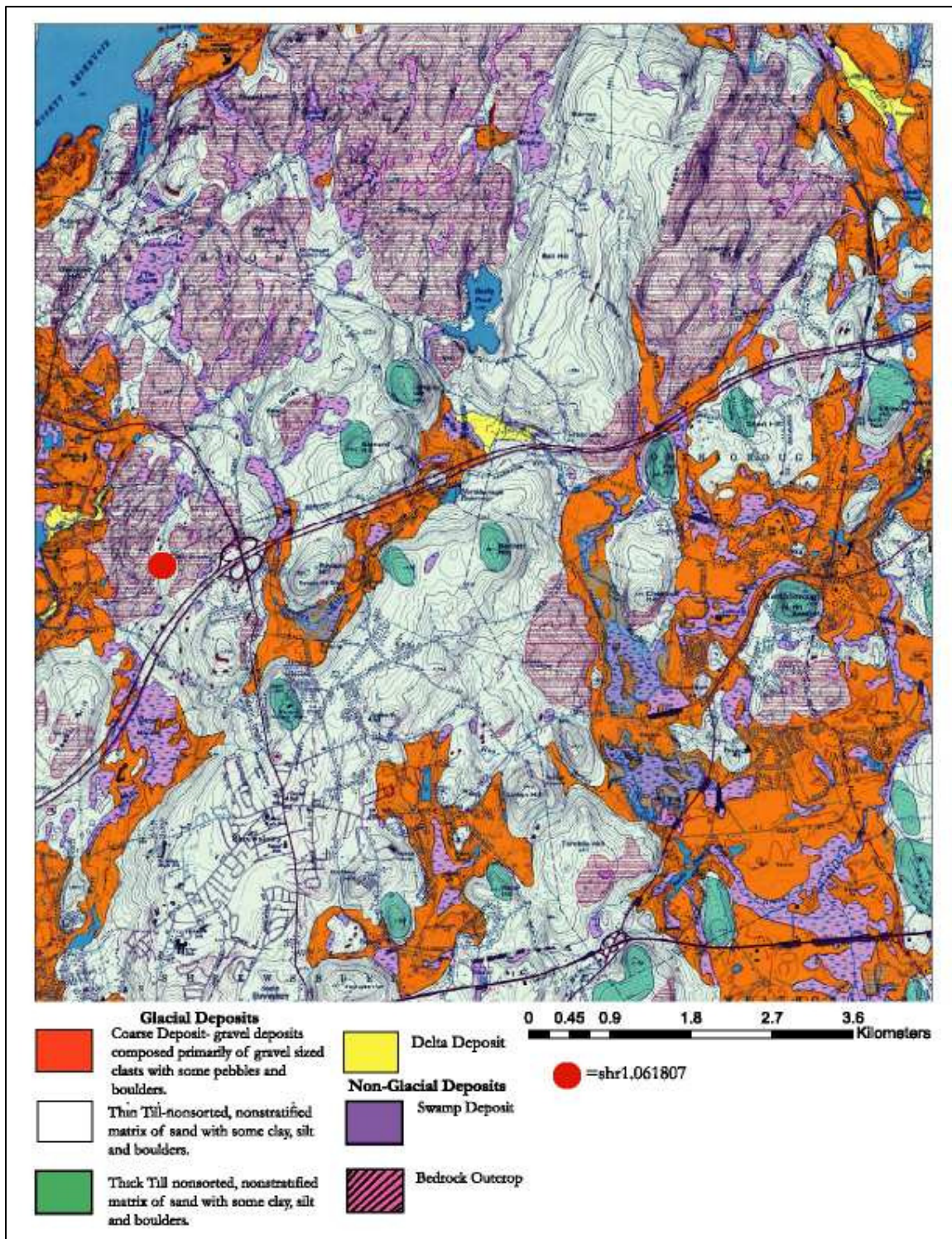


Figure 73. Surficial map of the Shrewsbury, MA area derived from the Shrewsbury Surficial Geological Quadrangle, Massachusetts (Stone and Stone, 2006).

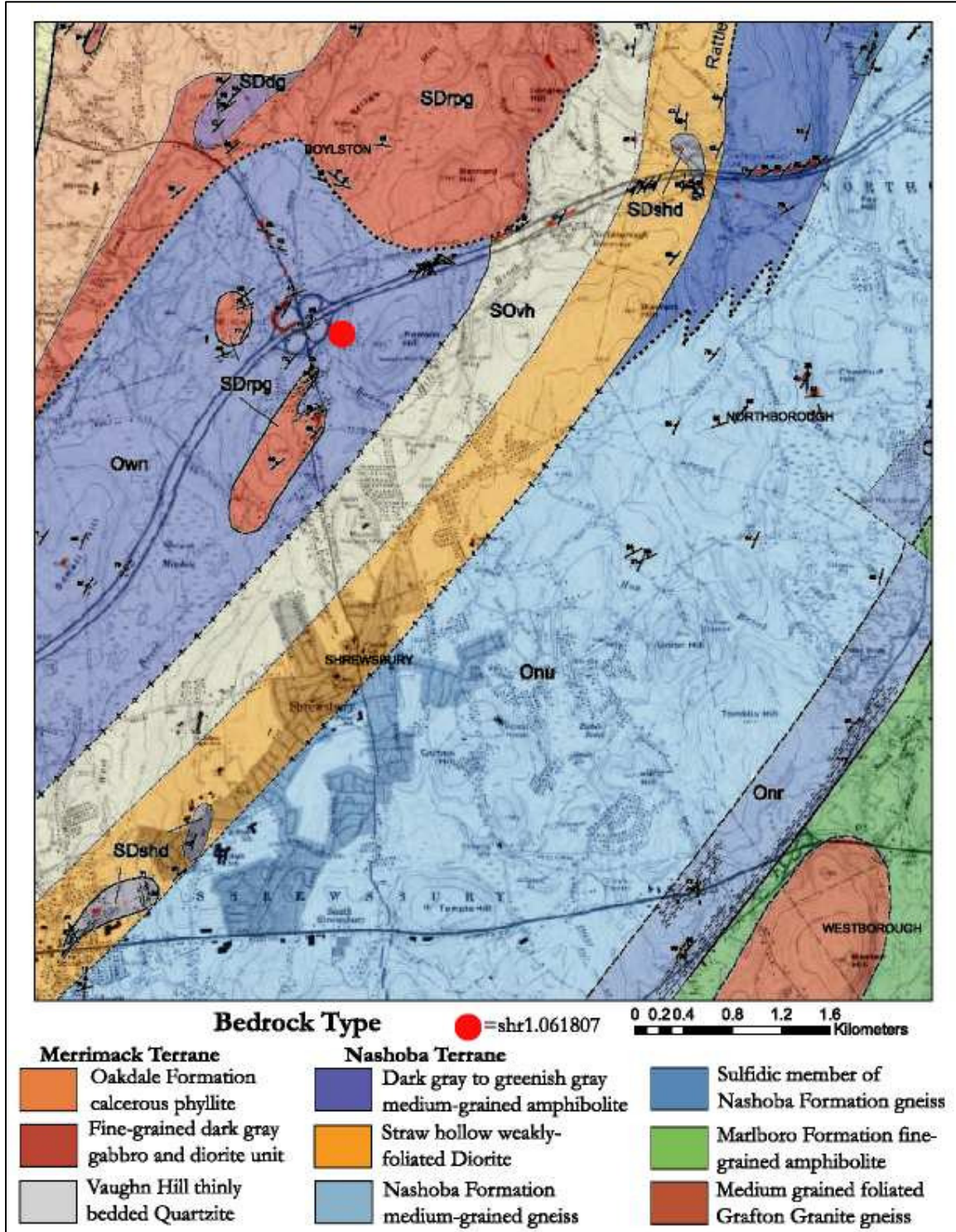


Figure 74. Bedrock map of the Shrewsbury, MA area derived from the Shrewsbury Bedrock Quadrangle, Massachusetts (Kopera et al., 2006).

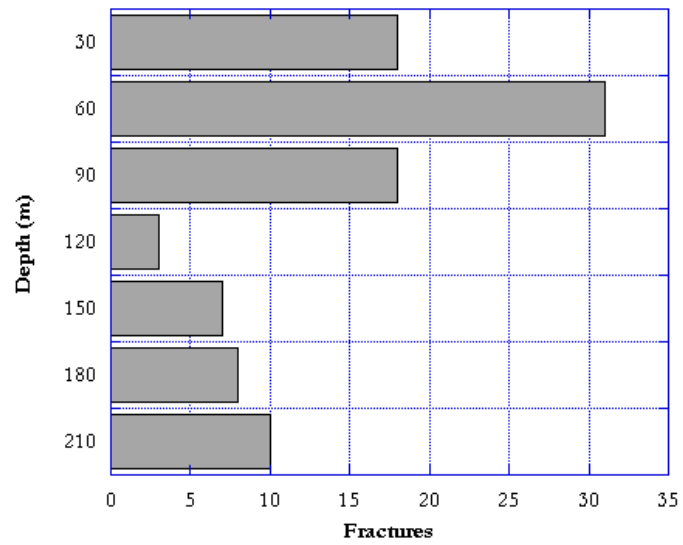


Figure 75. Histogram of fractures versus depth in the shr1.061807 well.

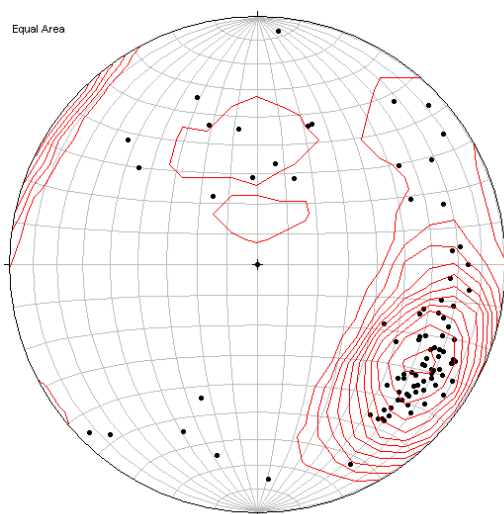


Figure 76. Kamb contour plot of fractures measured in shr1.061807 (n=95).

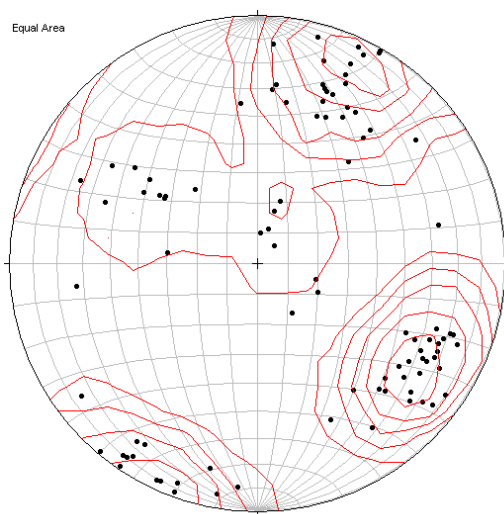


Figure 77. Kamb contour plot of fractures measured at outcrop "sh0177" in the Nashoba Formation (n=97).

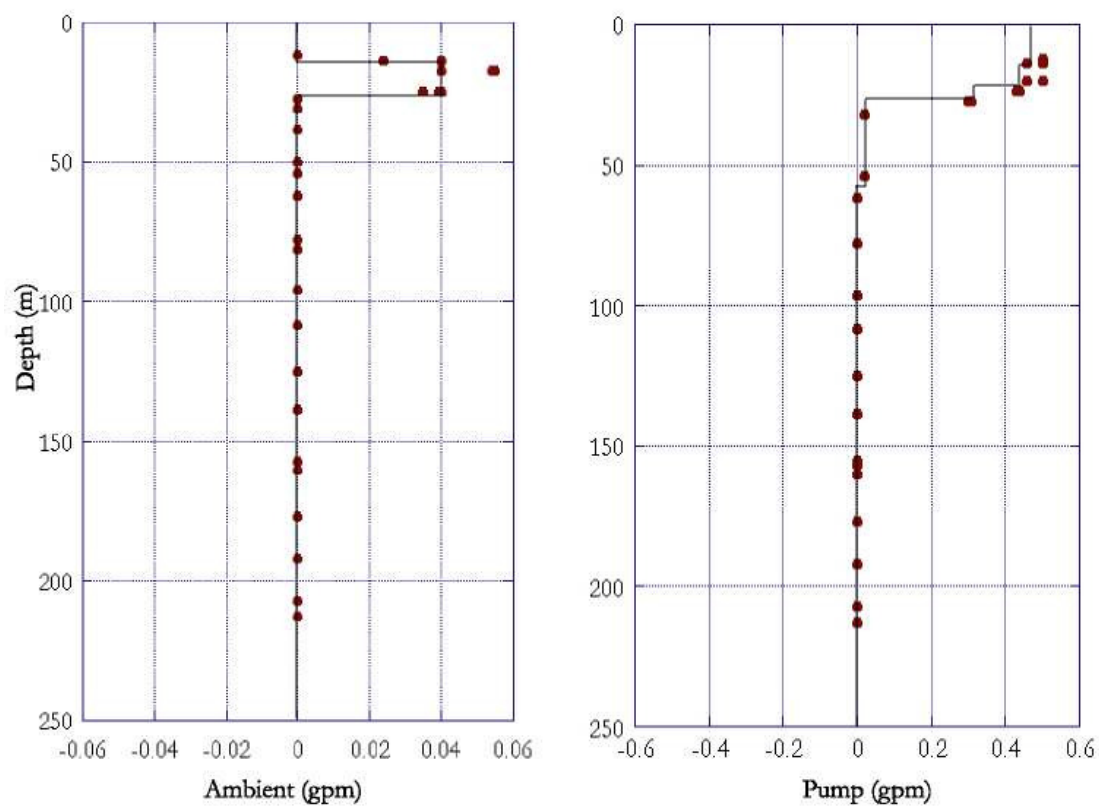


Figure 78. Plot of borehole flow profile from shr1.061807. Data collected using Heat Pulse flowmeter.

1.9.10 Kids-A-Lot Daycare Stow, MA

Kids-A-Lot daycare is located off of Red Acre Rd in Stow, MA. The daycare commissioned the drilling of a bedrock rock well in the spring of 2007 due to the decreasing productivity of the existing bedrock well on site. The well ID is sto1.052207 and it is at an elevation of approximately 74 meters above sea level. The well was logged from May 22, 2007 through May 24, 2007. The well yielded 80 gallons per minute. The well site is at the top of small hill with swampy lowland at the bottom.

There is approximately 6 meters of surficial overburden at the site. The surficial material is a thin nonsorted, unstratified glacial till with some clay, silt and boulders (Figure 63). The bedrock is an unnamed amphibolite-gneiss unit. It is primarily a fine to medium-grained hornblende-actinolite-biotite-quartz-plagioclase orthogneiss with strongly defined lineation.

The well is 91 meters deep, the second shallowest well in the suite; over that length 62 fractures were identified and measured. The frequency of fractures in the well decreases with depth over the upper 75 meters however there is a significant increase below that depth (Figure 79). There are three dominant fracture orientation sets in the subsurface: a northeast striking set, an east-northeast trending tectonic joint set and a subhorizontal unloading joint set (figure 80). At the nearest outcrop there was a northeast trending set and a minor northwest striking set (Figure 81).

The water level was 2.2 meters below the ground surface at the outset of logging. The pumping test data for this well was unfortunately lost following the HPFM tests however during those tests seven fractures were flowing, which is 11% of the total. They were located at 11.7 (257°, 79°), 14.6 (231°, 66°), 16.5 (270°, 61°), 20.5 (264°, 59°), 24.7 (249°, 59°), 81.8 (321°, 15°) and 83.9 (303°, 18°) meters depth (Figure 82). Two of the flowing fractures were subhorizontal unloading joints and the remaining five were FPF joints. This distribution is fairly unique for the Nashoba, as most wells have tectonic joints contributing to flow in the well. This well was additionally unique in that during pumping two separate flow systems developed in the well. In the lower system, groundwater entered the well at 16.5 meters depth and flowed downward and out of fractures at the bottom of the well. This was also observed under pumping conditions. The second flow system consisted of two fractures at 14.6 and 11.7 meters which yielded the ½ gallon per minute under pumping conditions. It is unclear if these two systems are hydrologically related.

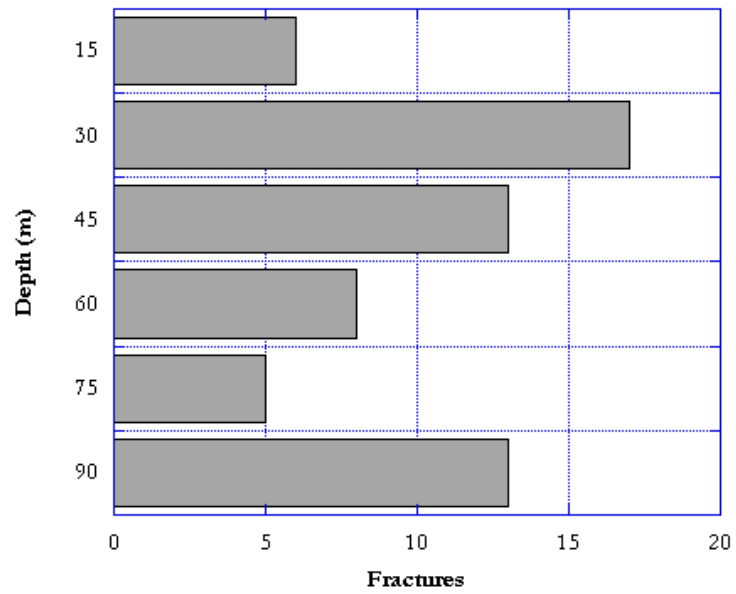


Figure 79. Histogram of fractures versus depth in the sto1.052207 well.

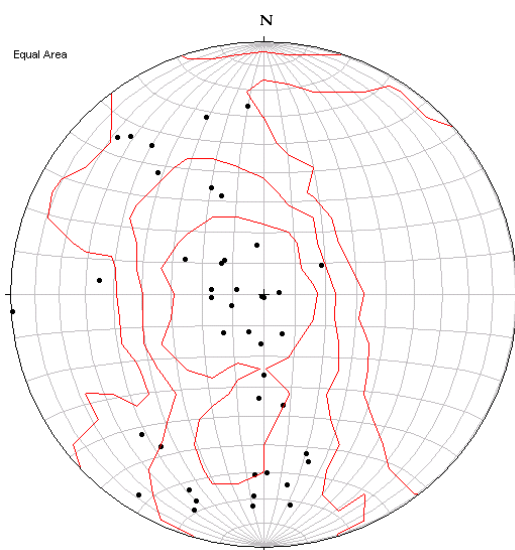


Figure 80. Kamb contour plot of fractures measured in well sto1.052207 (n=62).

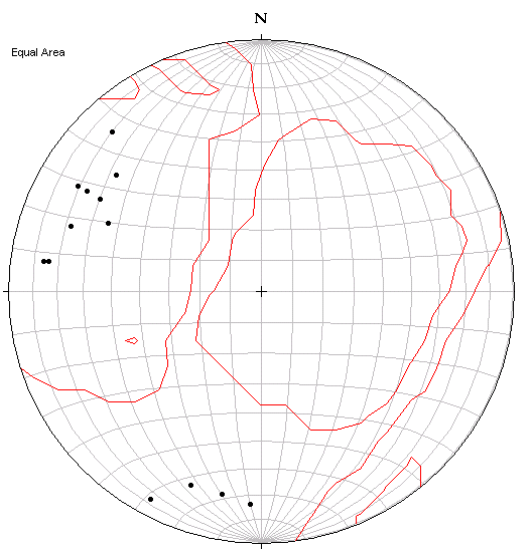


Figure 81. Kamb contour plot of fractures measured at outcrop "ma0277" in the Nashoba Formation (n=13).

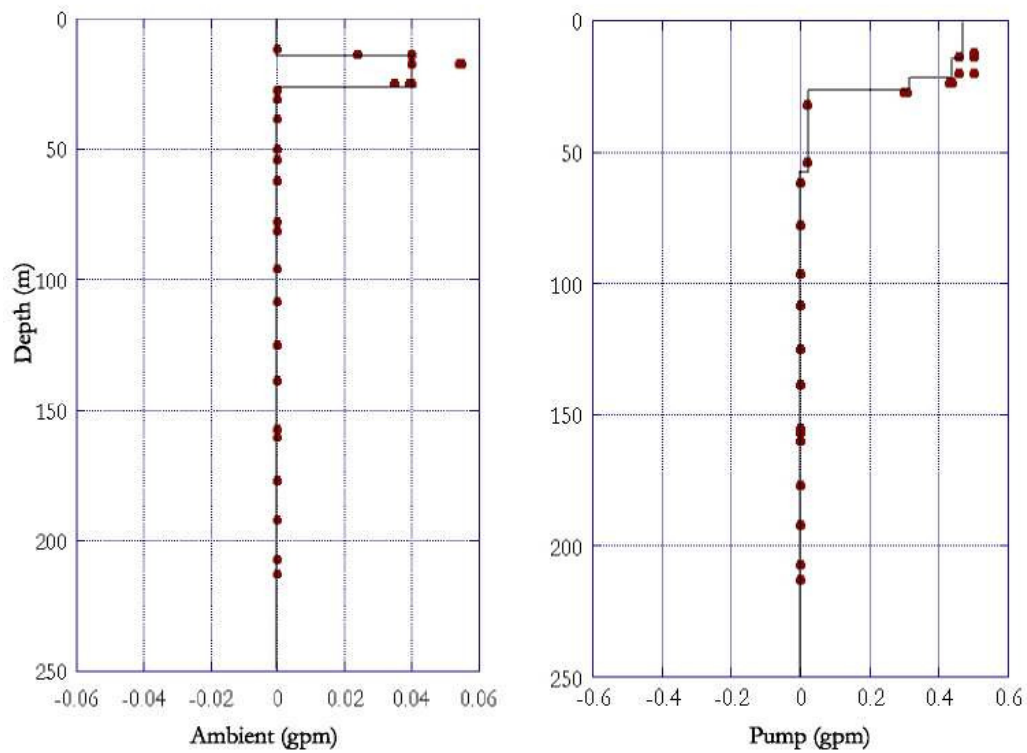


Figure 82. Plot of borehole flow profile from sto1.052207. Data collected using Heat Pulse flowmeter.

1.9.11 Blackstone National Golf Club Sutton, MA

Upon construction of the Blackstone National Golf Club the management had a series of wells drilled to provide irrigation. One well did not yield enough groundwater to be useful for day to day use; this well was logged from July 10 through July 13, 2007. The well ID is sut1.071007 and it has an elevation of 178 meters above sea level. The well is at the base of a large naturally occurring and there is a perennial stream and swamp directly next to the well. The well is purported to be 243 meters deep, however the cap of the well was broken off and the well has been exposed to the elements for a number of years. As a result, the well is currently 232 meters deep.

There is approximately 2 meters of disturbed overburden. Due to the location of the well it is likely that the material is composed of disturbed glacial materials. The bedrock at the site is dark-gray to greenish-gray medium-grained amphibolite (Figure 83). The well lies less than one km from the Bloody Bluff Fault zone.

Over the 232 meter length there were 52 fractures measured. The frequency of fractures decreases significantly with depth in the well (Figure 84). There is a significant increase in fracture frequency at 120 meters. This increase is associated with a flow zone, so it is possible that the increase in frequency at this depth is related to a large fracture zone which is contributing to flow in the well. There are eight subhorizontal unloading joints, 23 tectonic joints and 21 FPF in the well. There were two significant fracture sets a northeast striking set and a shallow dipping, northwest striking set (Figure 85). At the nearest outcrop, there were three fracture sets a northeast trending set, a northwest trending set and a subhorizontal unloading joint set (Figure 86).

The water level in the well was 2.7 meters below the ground surface at the outset of pumping. The well was pumped at $\frac{1}{2}$ gallon per minute for HPFM tests, unfortunately that data is not available. Five fractures were identified as flowing fractures during the HPFM tests which is 10% of the total. The flowing fractures were at 7.0 (100° , 51°), 16.8 (317° , 37°), 32.6 (145° , 15°), 116.7 (334° , 43°), and 136.9 (335° , 42°) meters depth (Figure 87). There are three FPF, one tectonic and one subhorizontal fractures contributing to flow.

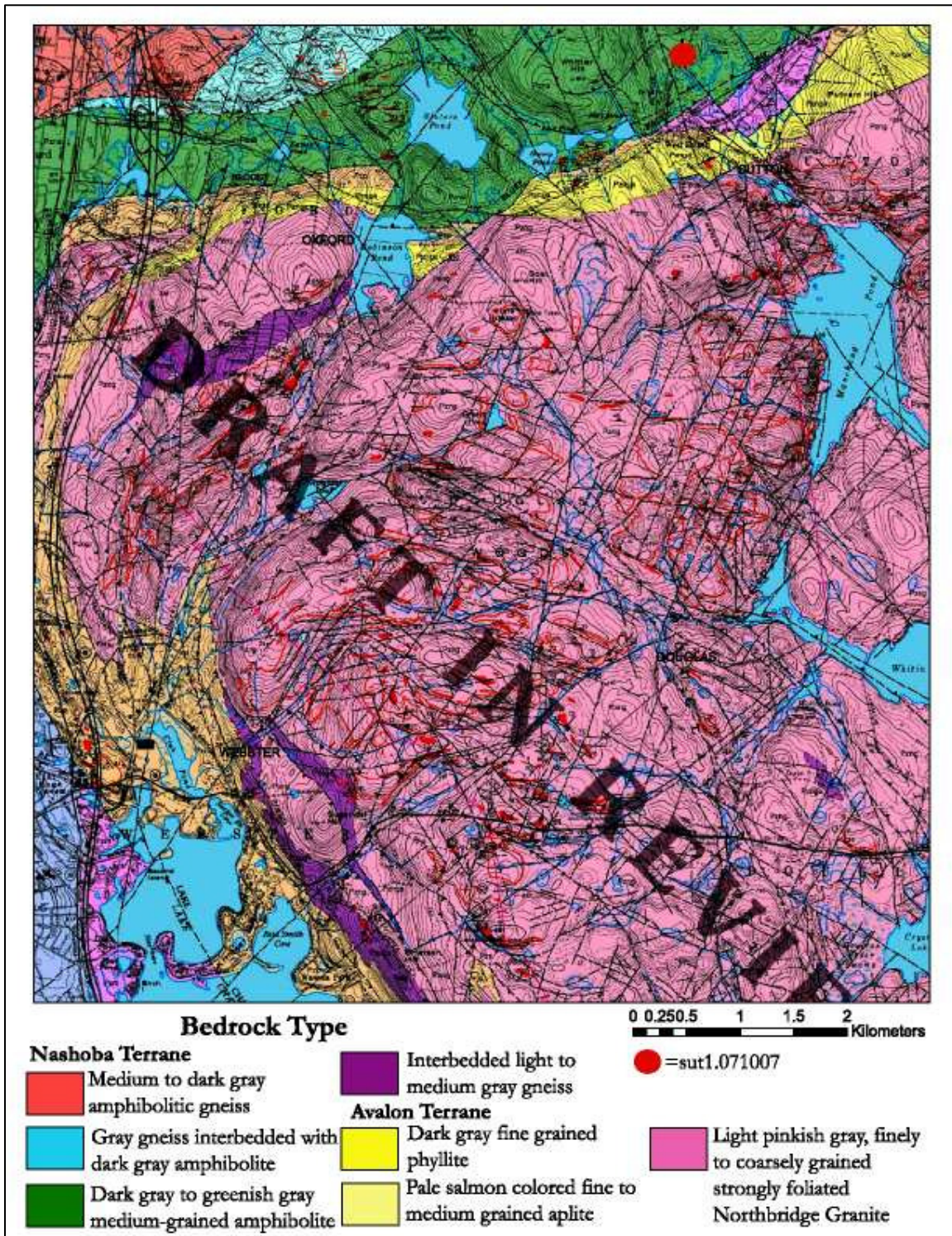


Figure 83. Bedrock map of the Sutton, MA area derived from the Grafton Bedrock Quadrangle, Massachusetts (MA State Geologist's Office).

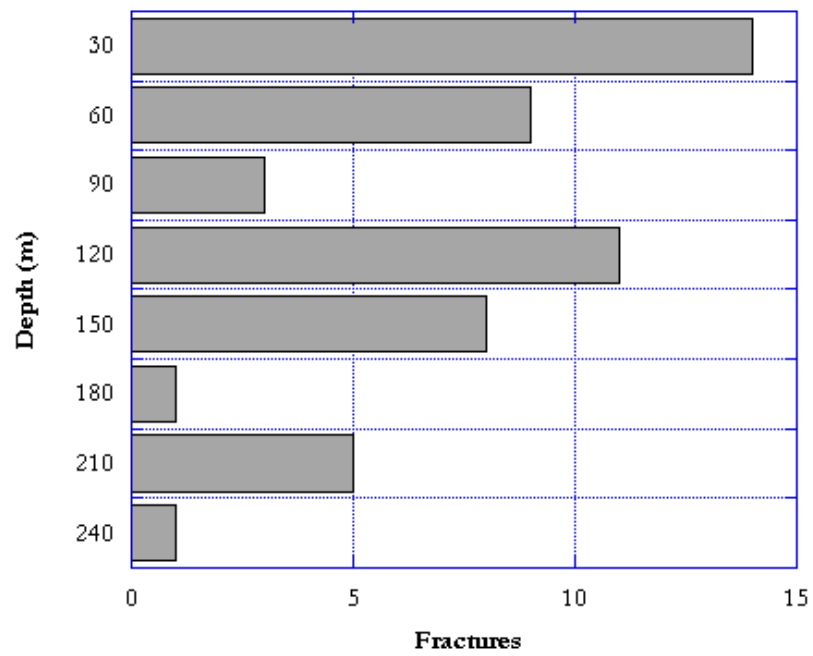


Figure 84. Histogram of fractures versus depth in the sut1.071007 well.

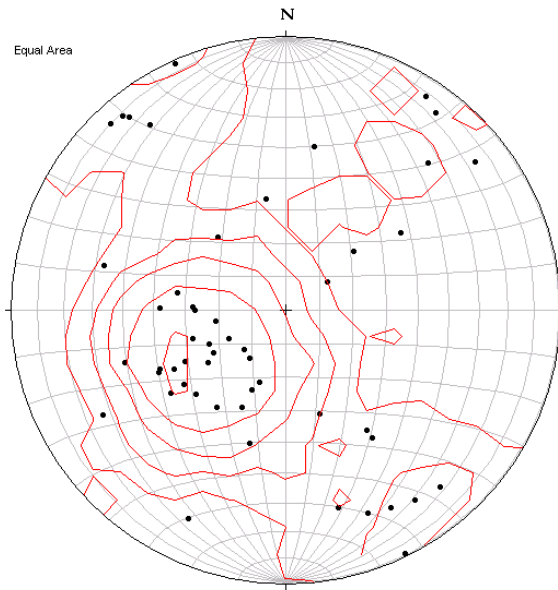


Figure 85. Kamb contour plot of fractures measured in sut1.071007 (n= 52).

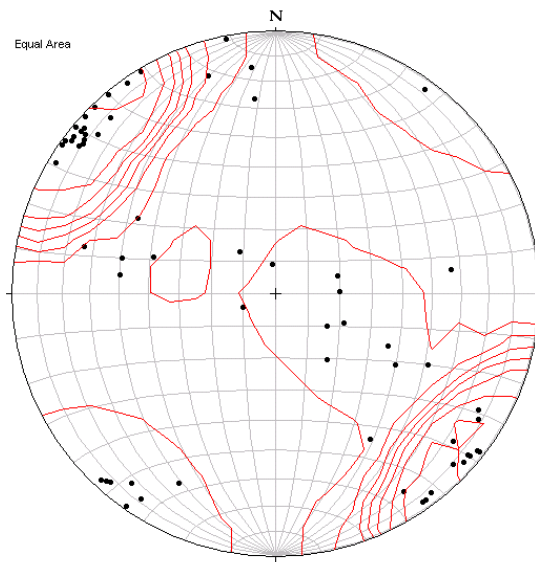


Figure 86. Kamb contour plot of fractures measured at outcrop "sh0408" in the Nashoba Formation (n=63).

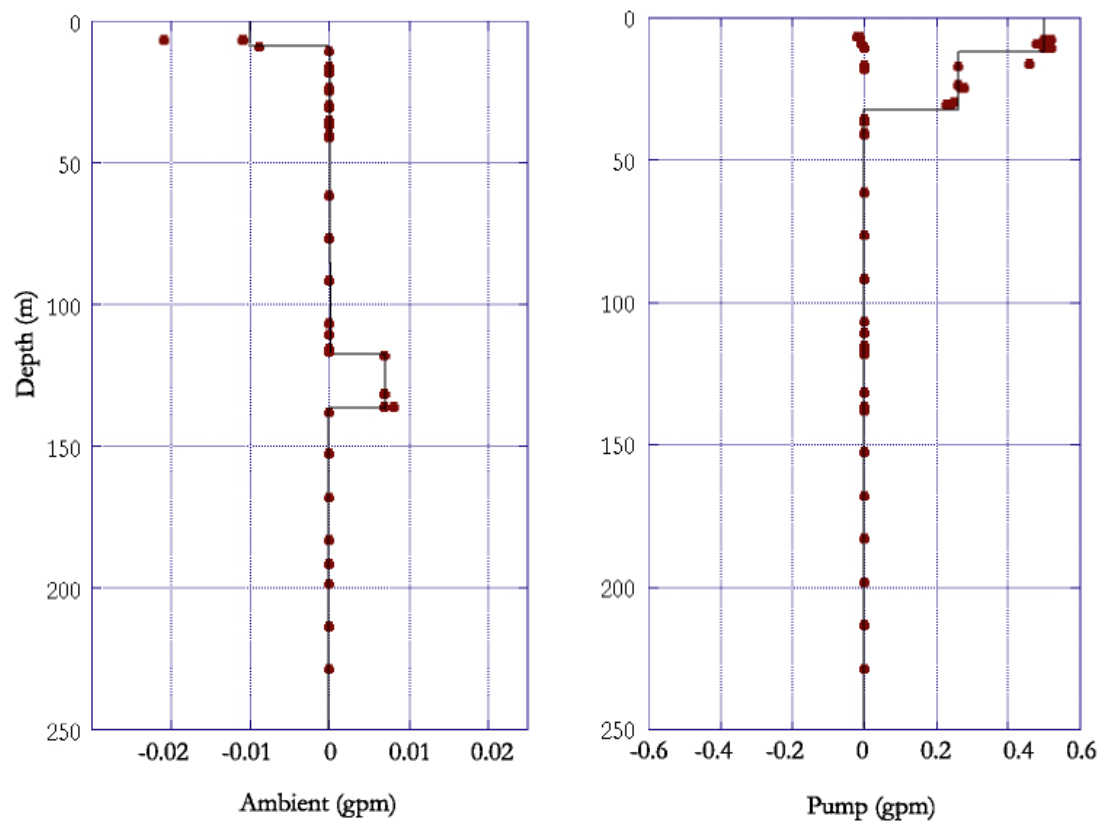


Figure 87. Plot of borehole flow profile from sut1.071807. Data collected using Heat Pulse flowmeter.

1.9.12 Rockport PWS Rockport, MA

Two wells were logged for this project outside the Nashoba Terrane. These wells, with IDs roc1.081507 and roc2.082107, were drilled as public water supply wells for the town of Rockport, MA. The wells are less than 100 meters apart and both are less than 100 meters from two surface water reservoirs. The town drilled the wells to supplement existing reservoirs. The wells are only seven meters above sea level. In pumping tests both wells yielded in excess of 60 gallons per minute.

The overburden is thin till that is composed mostly of nonsorted, nonstratified matrix of sand with some silt, clay, and boulders (Figure 88). The bedrock is Cape Ann Granite. The Cape Ann granite is an unfoliated, medium- to coarse-grained, leucocratic rock. The composition in the area of the wells is alkali-feldspar syenite (Figure 89).

Roc1.081508 The well roc1.081507 was logged from August 15, 2008 through August 20, 2008. The well is 136 meters deep with 6.1 meters of casing. There is approximately three meters of overburden at the well site. A total of 133 fractures were identified at the site. The frequency of fractures does not decrease with depth in this well (Figure 90). As the rock unit is granite there are no FPF in the Cape Ann, however two of the fractures were subhorizontal unloading joints and the rest were tectonic joints. There are three major fracture sets in this well: a northeast trending set, a northwest trending set and an east-west trending set (Figure 91a and b). There is also one minor north-south trending fracture set. The fracture patterns in this well correlate well with results from a nearby outcrop (Figure 92).

The water table in the well was approximately eight meters deep at the outset of the pumping test. The well was pumped at one gallon per minute for two hours and 20 minutes and was only drawn down 0.14 meters in that time. HPFM analysis of the well revealed five fractures were contributing flow to the well. The fractures were at 75 (167°, 55°), 88 (157°, 53°), 100 (54°, 72°), 105 (135°, 56°) and 133 (181°, 71°) meters (Figure 93). All of the flowing fractures were tectonic joints.

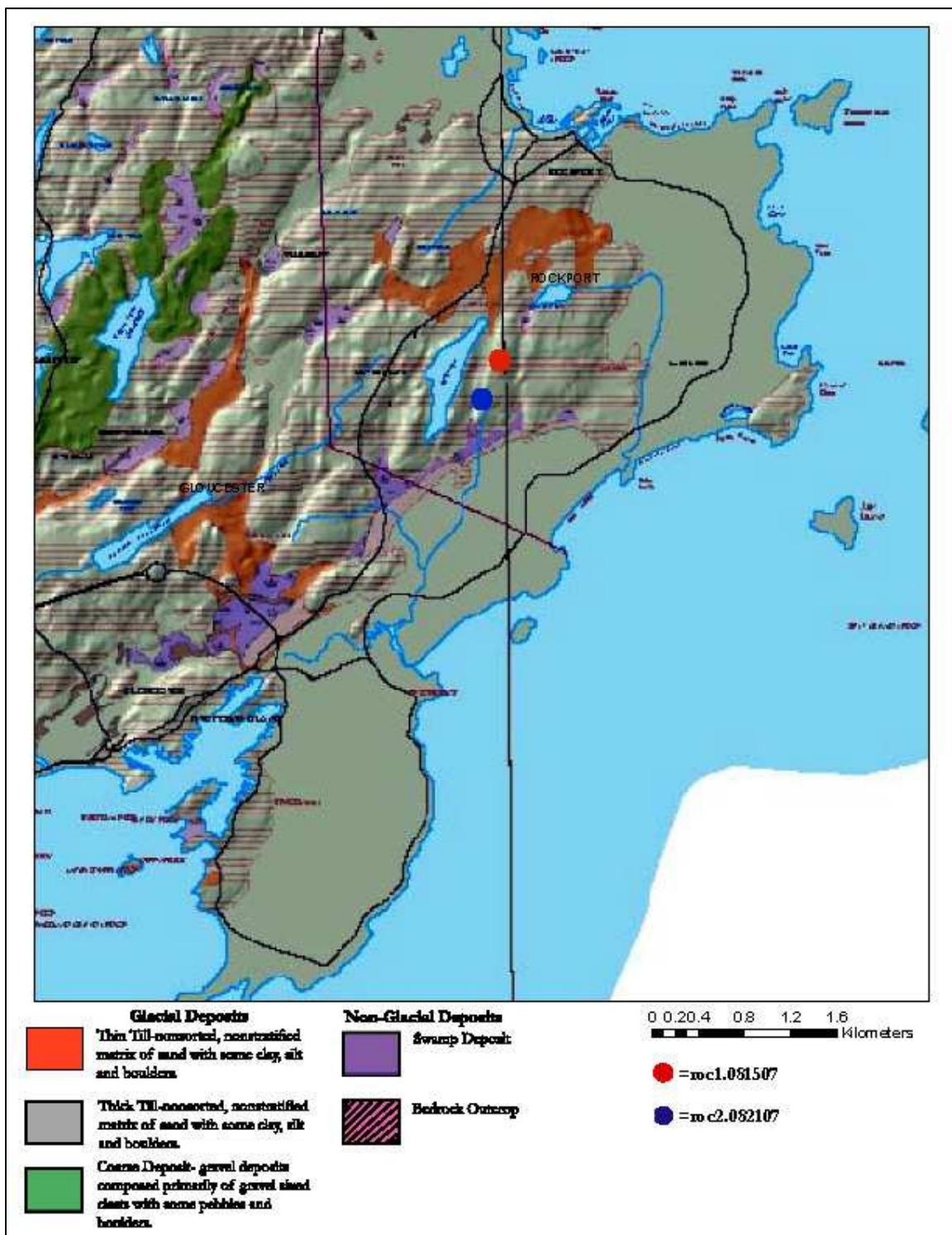


Figure 88. Surficial map of the Rockport, MA area derived from the Rockport-Gloucester Surficial Geological Quadrangle, Massachusetts (Stone et al., 2006).

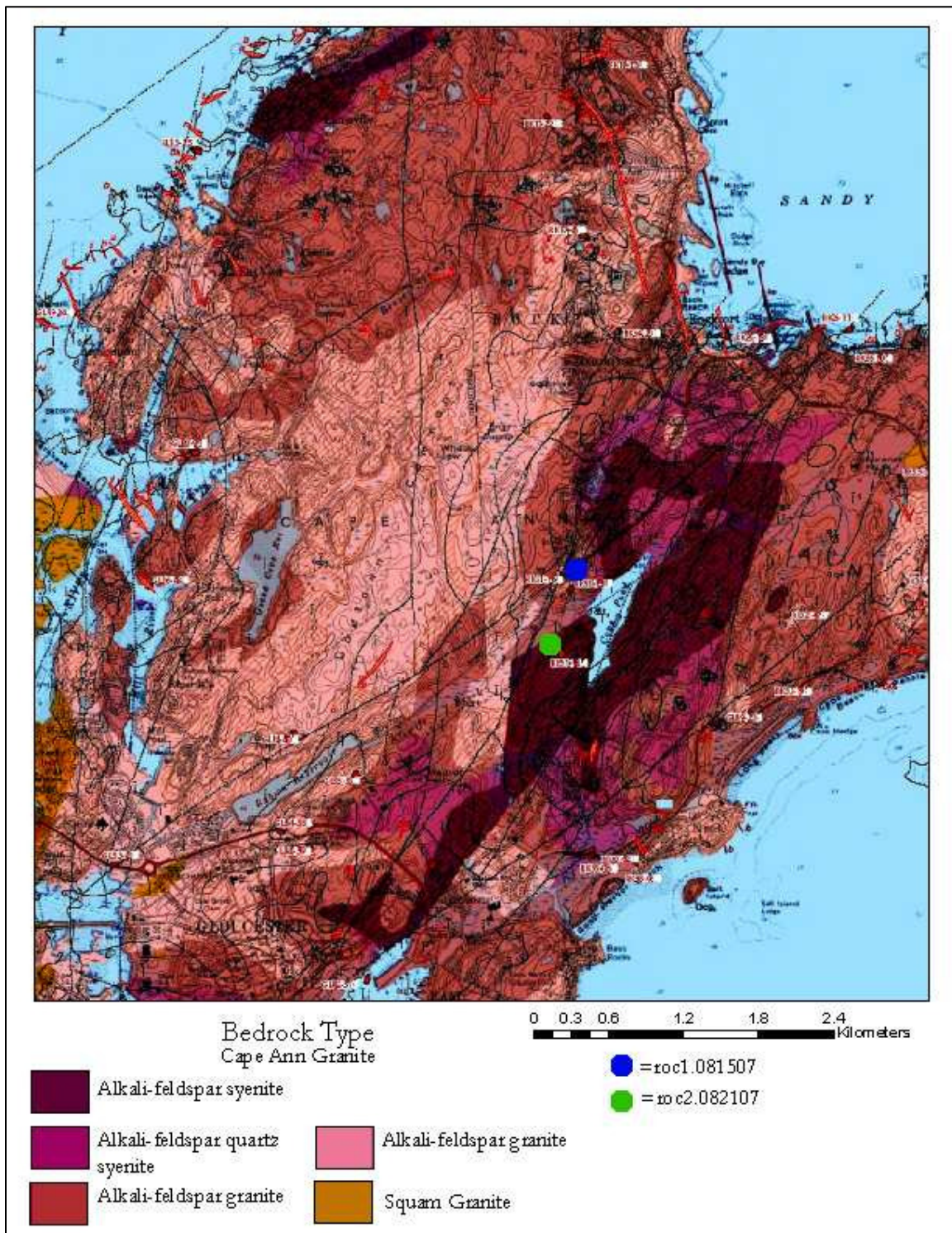


Figure 89. Bedrock map of the Rockport, MA area derived from the Rockport-Gloucester Bedrock Quadrangle, Massachusetts (Dennen, 1992).

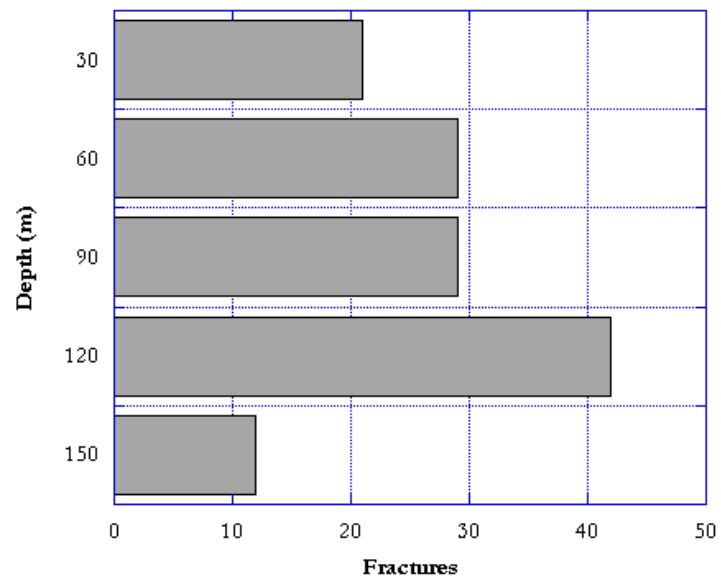


Figure 90. Histogram of fractures versus depth in the roc1.081507 well.

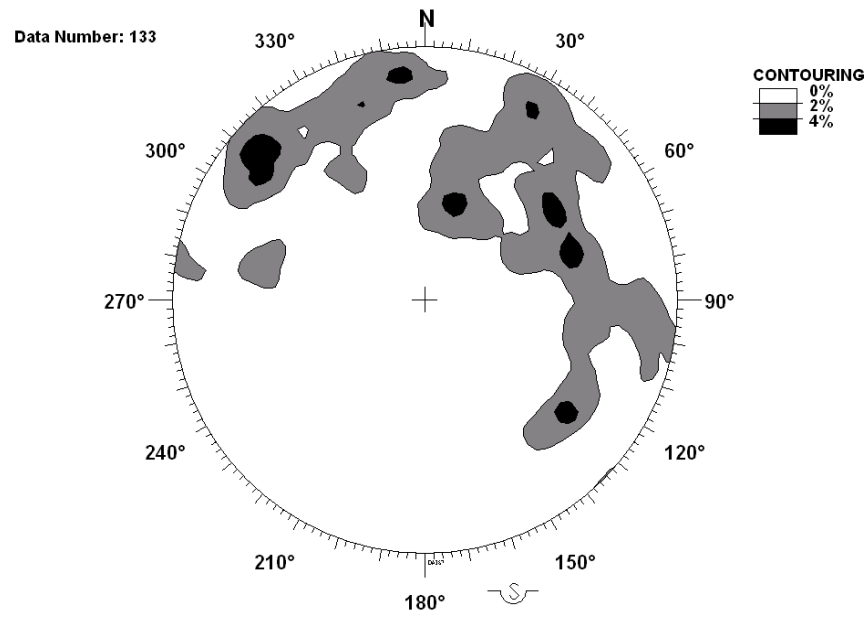


Figure 91a. Stereonet plot of fractures measured in roc1.081507 with a 2% contouring interval.

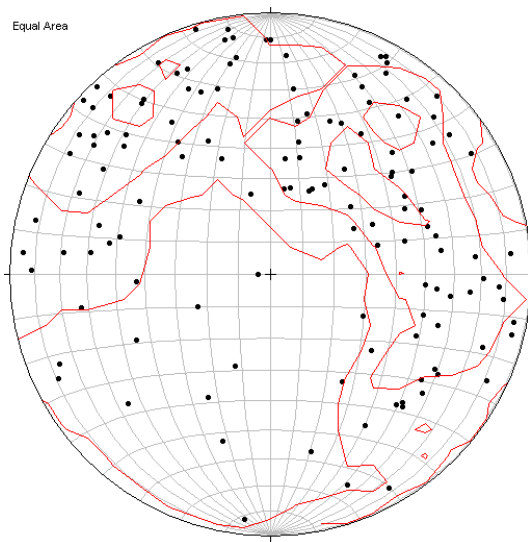


Figure 91b. Kamb contour plot of the fractures measured in roc1.081507 (n=133).

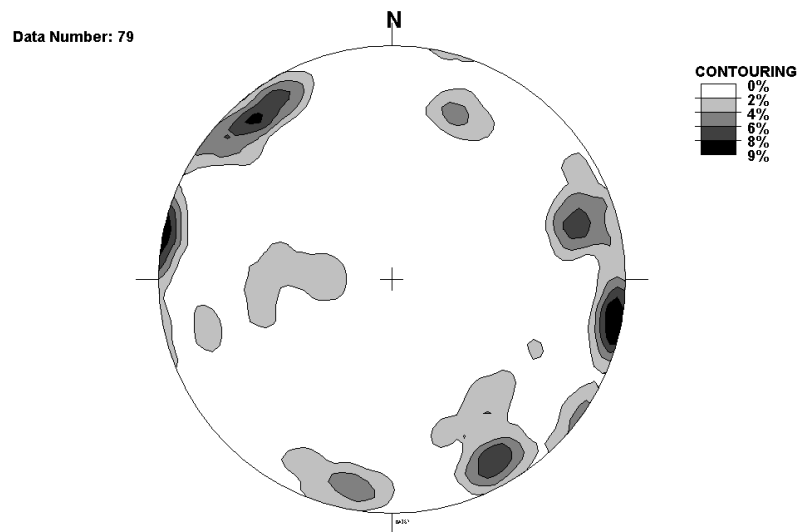


Figure 92 Stereonet plot of fractures measured in a nearby outcrop with a 2% contouring interval (n=79).

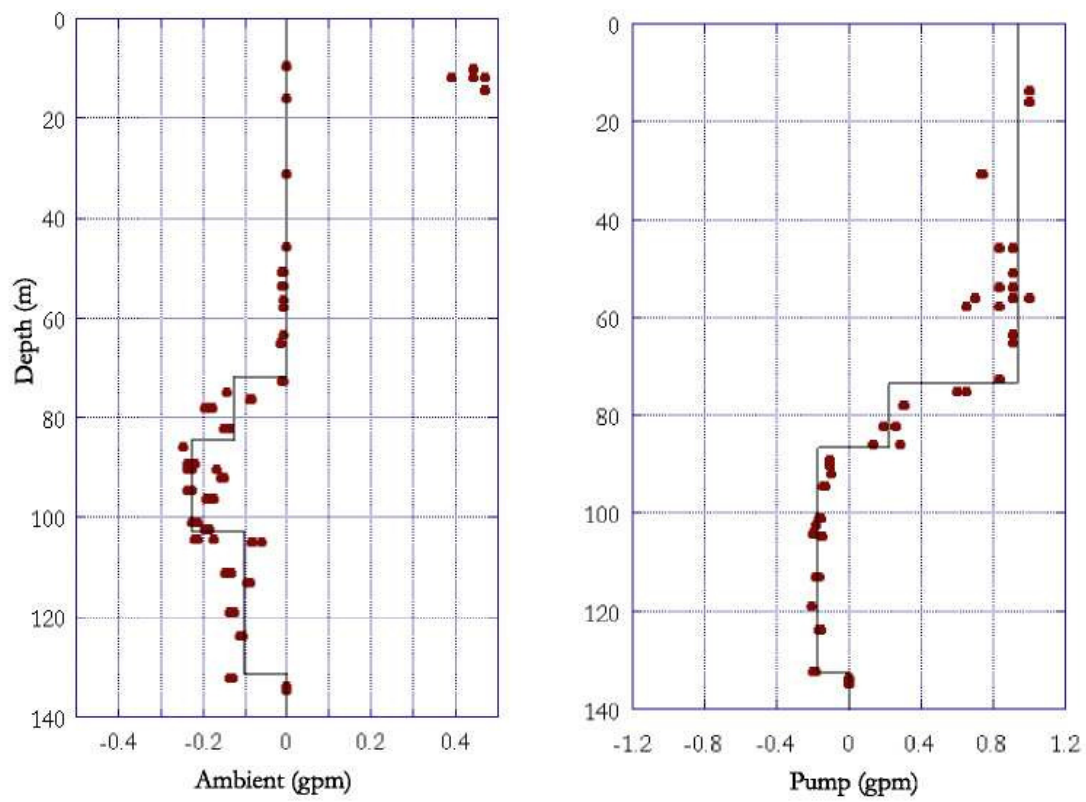


Figure 93. Plot of borehole flow profile from roc1.081507. Data collected using Heat Pulse flowmeter.

Roc2.082107 The roc2.082107 well was logged from August 21, 2007 through August 25, 2007. The well is 168 meters deep with 6.1 meters of casing. There was 3 meters of overburden at this site. A total of 127 fractures were identified in this well, and the frequency of the fractures decreases (Figure 94). As in the other Rockport well, there are no FPF fractures. There were two subhorizontal unloading joints and the remaining fractures are tectonic joints. There are two major fracture sets in this well: a north-south trending set and a smaller northeast trending set (Figure 95a and b). There is also a minor northwest trending set. Fracture sets identified at a nearby outcrop are generally consistent with the fracture sets identified in this well (Figure 96). Here there is a large north-south trending set, along with an east-west trending set.

The water table in the well was 12.3 meters deep at the outset of the pumping test. The well was pumped for two hours and 30 minutes during which the water level decreased only 0.8 meters. Five fractures were found to be contributing flow to the borehole in this well, which is approximately 6% of the total. The fractures were at 14 (60°, 38°), 52 (355°, 80.6°), 73 ((271°, 80.3°), 77 (264°, 30.6°) and 110 (225°, 77°) meters depth (Figure 97). All of the flowing fractures were tectonic joints.

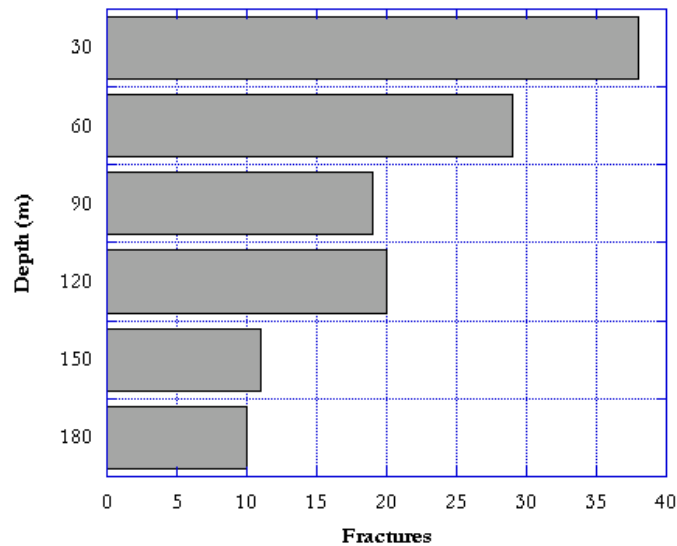


Figure 94. Histogram of fractures versus depth in the roc2.082107 well.

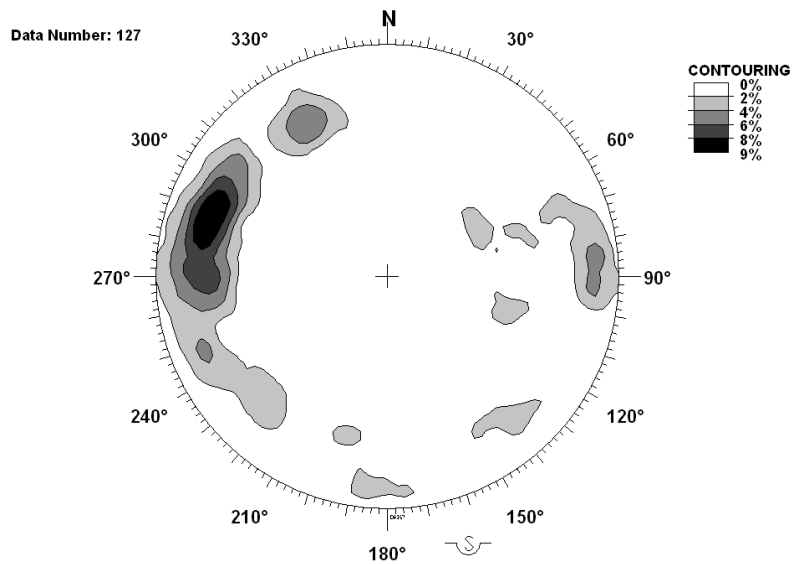


Figure 95a. Stereonet plot of fractures measured in roc2.082107 with a 2% contouring interval.

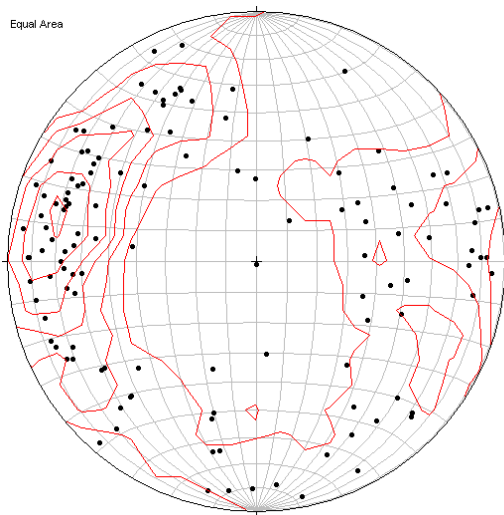


Figure 95b. Kamb contour plot of fractures measured in roc2.082107 (n=127).

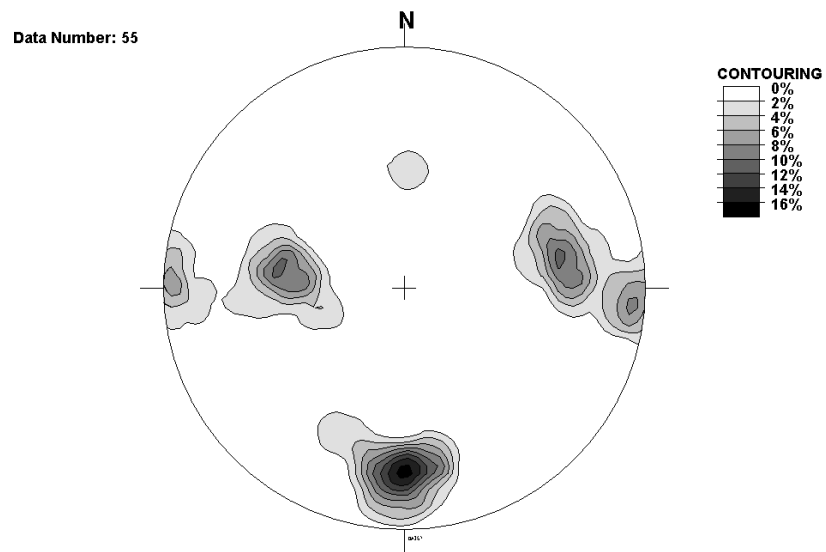


Figure 96. Stereonet plot of fractures measured at a nearby outcrop with a 2% contouring interval (n=55).

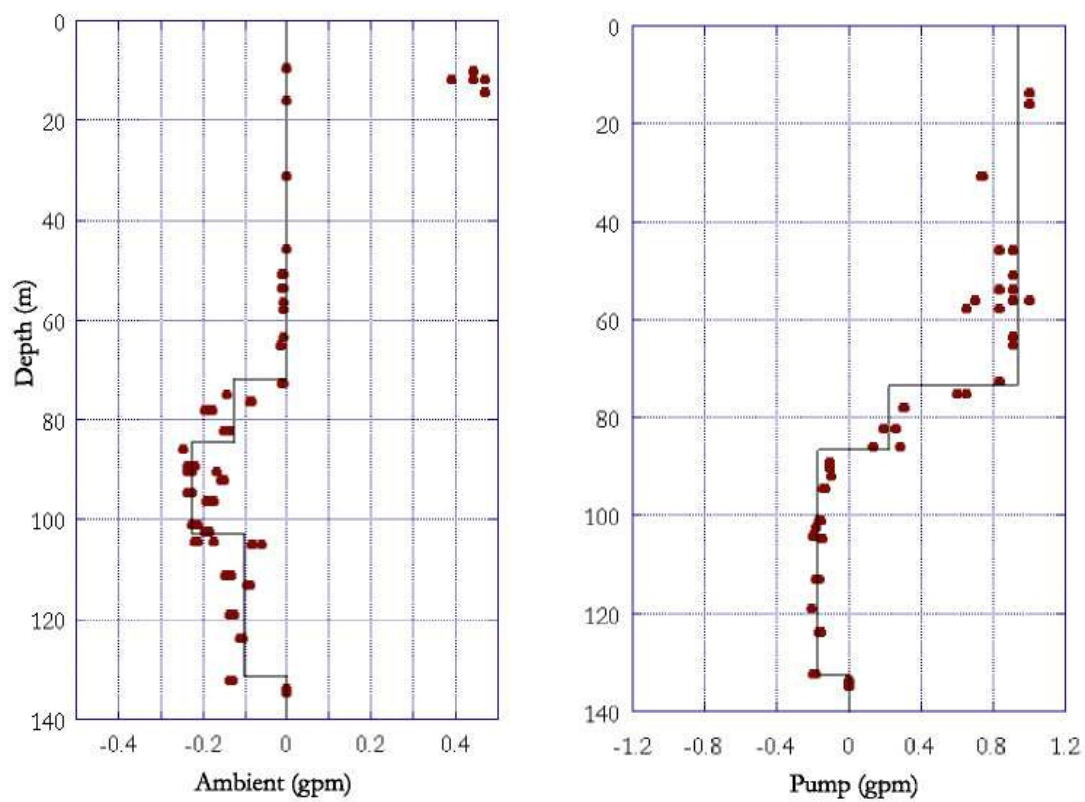


Figure 97. Plot of borehole flow profile from roc2.082107. Data collected using Heat Pulse flowmeter.

1.9.13 Coppermine Road Topsfield, MA

The well on Coppermine Rd in Topsfield, MA was drilled in 2002 for lawn maintenance at a private residence. The well was drilled 365 meters, or 1,200 feet, into bedrock and yielded less than one gallon per minute. The property sits at the edge of a 50 meter cliff overlooking a golf course and man-made swimming pond. The well ID is top1.080907 and it has an elevation of 13 meters above sea level. The well was logged from August 9 through August 14, 2007.

The site is at the top of a small hill composed of glacial materials which are 19 meters thick. The composition of this material is poorly sorted sand and gravel with some pebbles and boulders (Figure 98). The well casing is 23 meters deep. The bedrock is a medium to fine-grained light pink granodiorite that is located at the edge of the Nashoba Terrane (Figure 99). The well is in the Bloody Bluff fault zone and lies only meters from the mapped location of the fault.

Over the 365 meter length of the well 348 fractures were measured. The frequency of those fractures decreased considerably with depth in the well (Figure 100). Here most of the fractures are between 60 and 180 meters depth; there is a significant drop below 180 meters depth. Of the total number of fractures 9 were subhorizontal unloading joints and the remaining fractures were tectonic in origin. There are three major fracture sets in this well (Figure 101a and b). There is a north-northeast trending set, a northeast trending set, a north-northwest trending set and a northwest trending set. There is also a minor shallow dipping northeast trending set. There is no outcrop that can be used for comparison at the well due to the relative isolation of the well and the small size of the rock unit.

The water level in the well was 23.5 meters below the ground surface. This is likely due to a combination of extremely low yield and drawing down over many years from the nearby golf course. The depth of the water table and the low yield disallowed a pumping test at this site. The well was pumped at a rate of 1/4 gpm for approximately two hours and the well never reached a steady state. During HPFM tests under ambient conditions two flowing fractures were identified in the well at 72 and 141.4 meters depth (Figure 102). Both fractures were steeply dipping tectonic joints.

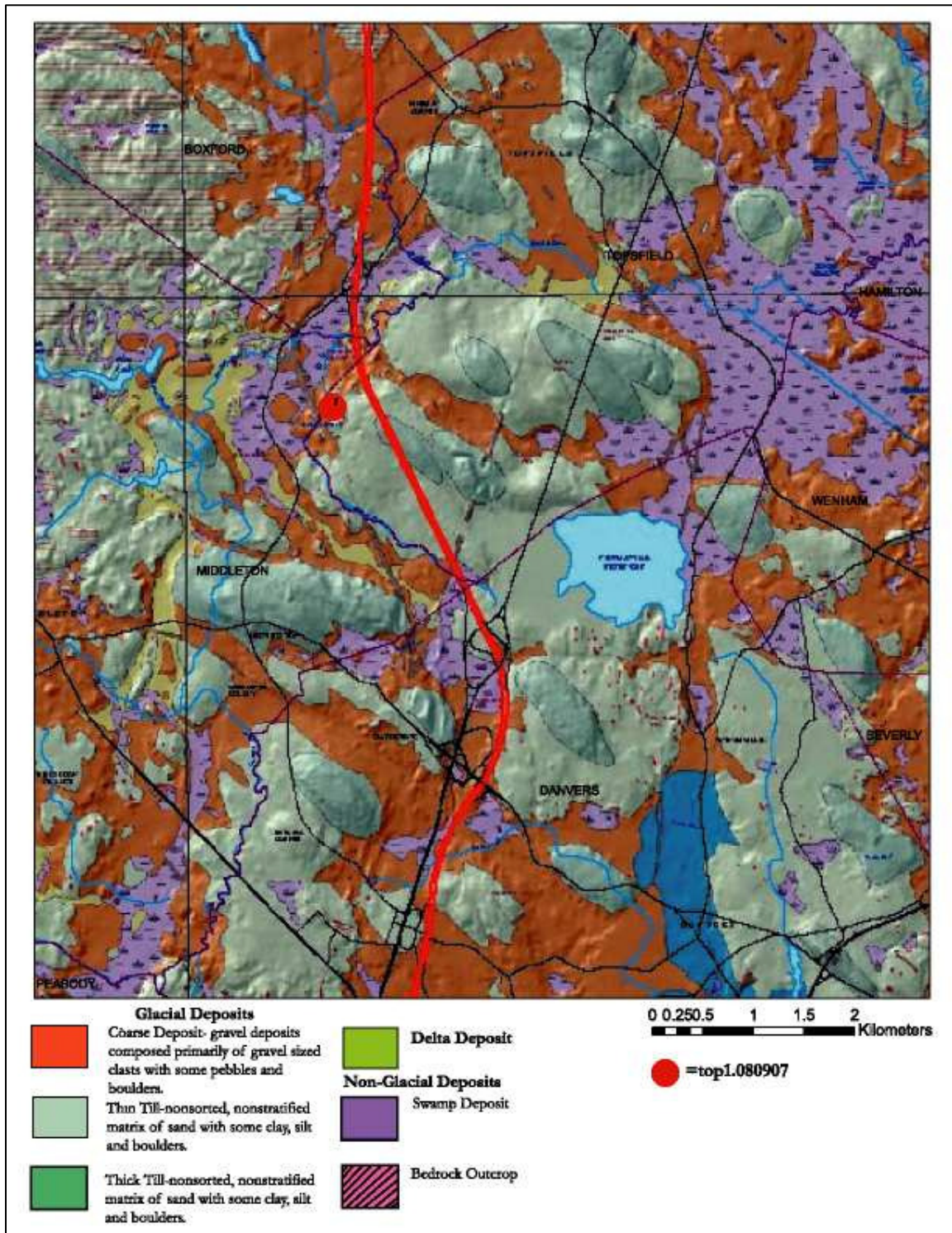


Figure 98. Surficial map of the Topsfield, MA area derived from the Georgetown Surficial Geological Quadrangle, Massachusetts (Stone et al., 2006).

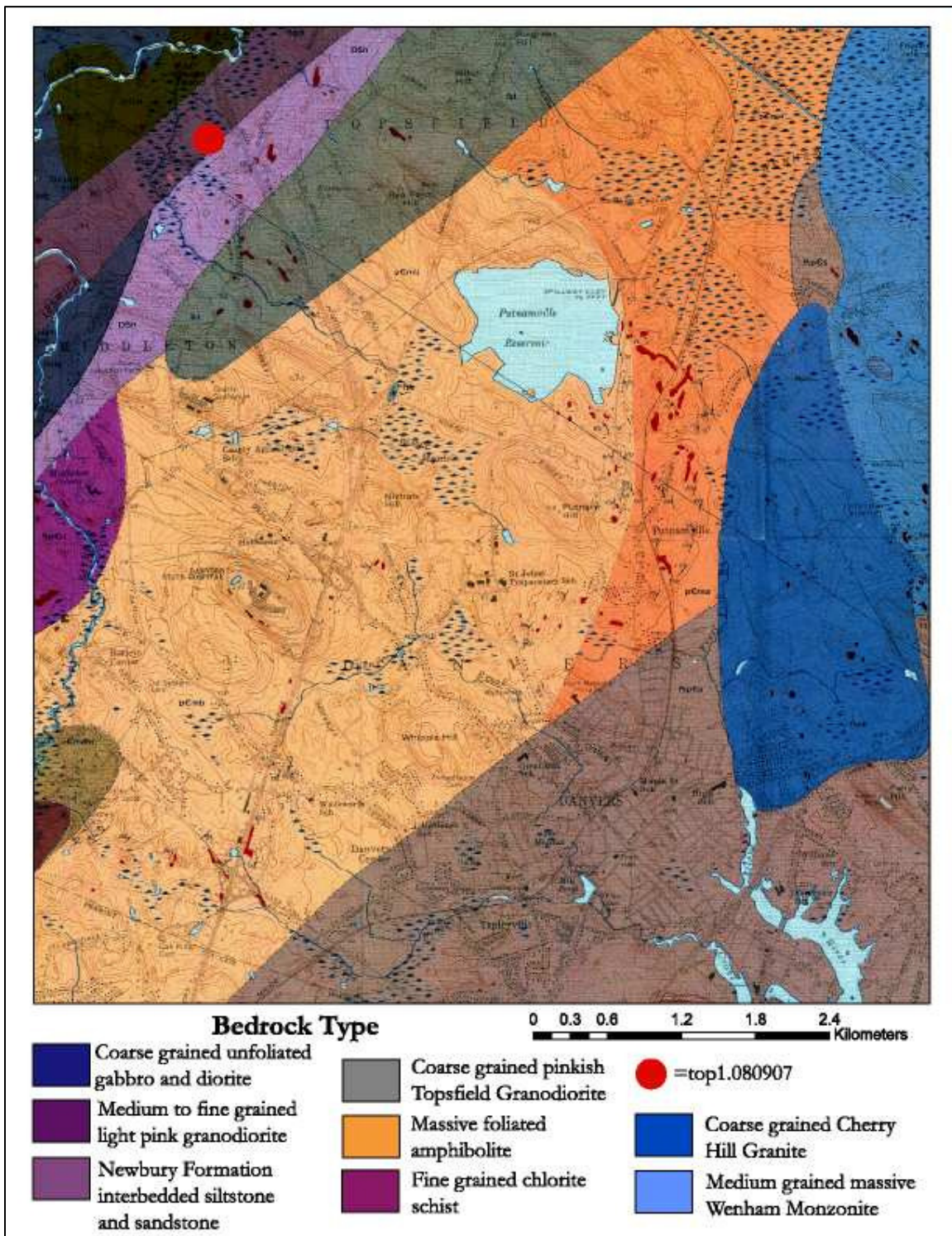


Figure 99. Bedrock map of the Topsfield, MA area derived from the Georgetown Bedrock Quadrangle, Massachusetts (Kopera et al., 2006).

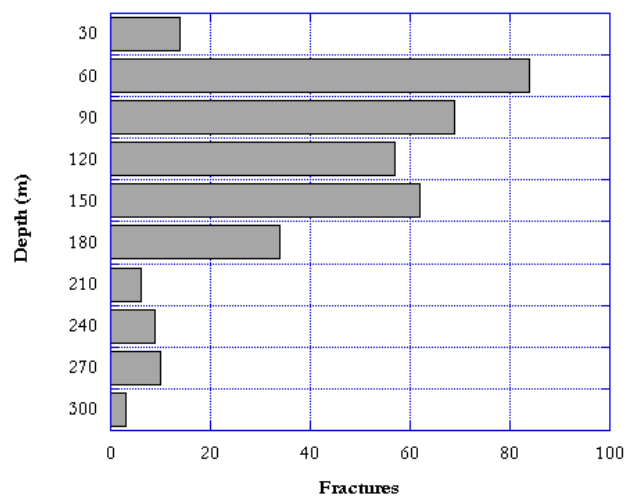


Figure 100. Histogram of fractures versus depth in the top1.080907 well.

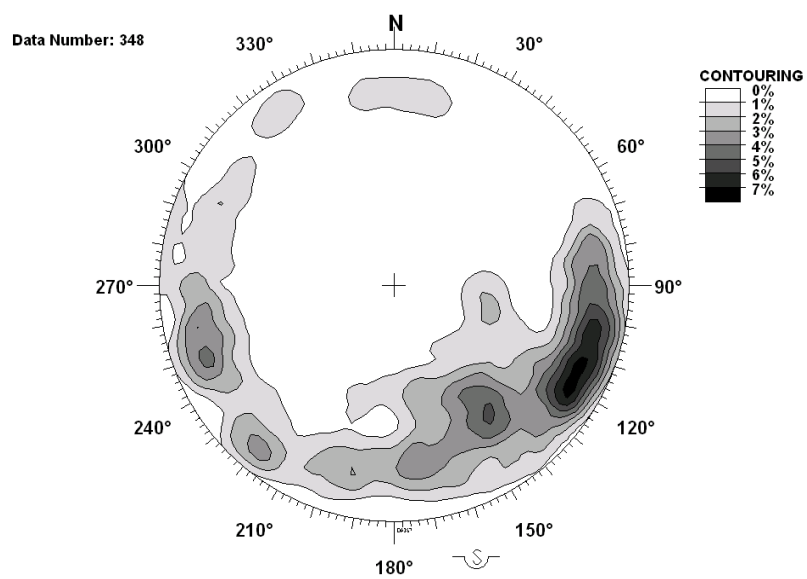


Figure 101a. Stereonet plot of fractures measured in top1.080907 with a 1% contouring interval.

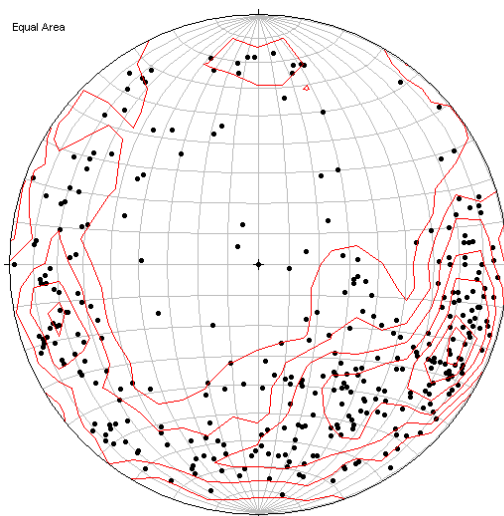


Figure 101b. Kamb contour plot of fractures measured in top1.080907 (n=348).

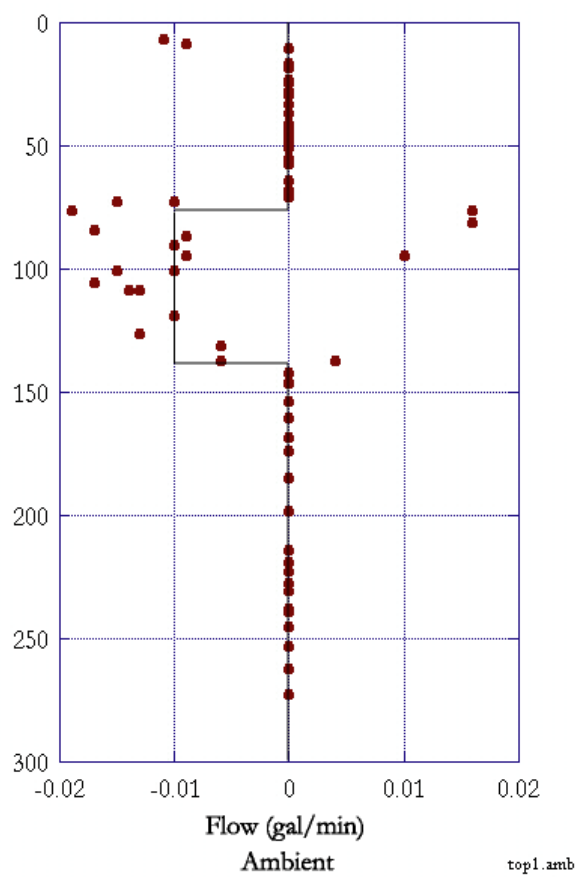


Figure 102. Plot of borehole flow profile from top1.080907. Data collected using Heat Pulse flowmeter.

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CHAPTER 2

UNDERSTANDING THE DEPTH AND NATURE OF DISCRETE FRACTURE FLOW IN THE NASHOBA TERRANE, EASTERN MASSACHUSETTS

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2.1 Abstract

Igneous and metamorphic rock units are considered marginal aquifers yet they are a significant source for potable drinking water in many areas worldwide, and use of these systems is on the rise. The Nashoba terrane is a northeast-trending, fault-bounded, accreted terrane located in eastern Massachusetts, USA. A comprehensive borehole geophysical study was undertaken in the Nashoba to identify and characterize discrete fracture flow in the terrane. Seventeen wells were logged for this study in three rock types: schist, amphibolite and granite. Total depth and groundwater yield of wells was highly variable throughout the study.

A total of 1,905 fractures were identified in the seventeen wells studied in the Nashoba Terrane, of which 4% were found to be contributing to flow in the boreholes. Three primary fracture types were identified: northeast-trending foliation parallel fractures (FPF), tectonic joints, and subhorizontal unloading joints. Several dominant fracture orientation sets were also prevalent throughout the terrane including east-west trending and north-south trending fracture sets. Dominant fracture orientations were rock type specific; however there was no noted correlation between rock type and flow. The frequency of fractures in the Nashoba terrane was found to decrease significantly with depth. The magnitude of flow from fractures also decreases with depth. Observations from this study have important implications for our understanding of the depth and nature of fluid flow in crystalline bedrock environments.

2.2 Introduction

Contamination and overuse of surficial aquifers, as well as expanding population and drought have spurred the search and development of groundwater resources in crystalline bedrock aquifers (Shapiro, 2002). Fractured crystalline rocks are characterized by low matrix permeability and extremely low porosity ($<<1\%$) and strongly preferential flow paths. Due to the virtually impermeable matrix, flow in these systems is primarily constrained to discrete features including fracture networks and large scale features such as faults. These factors make the rock and aquifer properties of these systems very different from classically studied aquifer materials (cemented and uncemented clastic sediments). As a result much is still not known about the flow systems of these aquifers. In recent years, progress has been made in both equipment, such as borehole geophysics, and characterization techniques which have advanced our understanding of these systems significantly.

A borehole geophysical study of the Nashoba terrane was undertaken in 2007 by the University of Massachusetts-Amherst in conjunction with the Massachusetts State

Geologist's office and the USGS-Northborough, MA. Borehole geophysical tools were used in previously drilled bedrock wells to identify fracture characteristics of the Nashoba terrane. The goal of this paper is to address the distribution of fractures with depth in the terrane, and the implications of this distribution for regional fluid flow.

2.3 Geologic and Hydrologic Setting

The Nashoba Terrane is a fault-bounded block of high-grade, steeply dipping metavolcanic and metasedimentary rock, overlain by a thin veneer of glacial sediments (5 to 50 meters thick), located in eastern Massachusetts, U.S.A. The Nashoba is northeast trending, extending from Oxford, MA to the Gulf of Maine south of Newburyport, MA (Figure 1). The rock units within the Nashoba zone are considered to be part of a single lithotectonic entity because common lithologies are interlayered and because the zone is flanked by terranes of disparate lithology and structure. The seminal characterization of the Nashoba was completed by Richard Goldsmith (1991).

The unit is bounded to the west by the Clinton-Newbury fault zone and to the east by the Bloody Bluff fault zone. There are five primary rock units within the Nashoba terrane; the units to the west are largely metasedimentary, while the units to the east are largely metavolcanic. The most common rocktype is schist (Nashoba Formation Schist and Tadmuck Brook Schist); there are also several amphibolite units (Marlborough Formation). Additionally, there is also extensive granitic intrusion throughout the terrane, which is predominantly in the northeastern portion of the terrane (Andover Granite). There are also several large faults throughout the Nashoba Terrane which bound the various units.

The climate of Massachusetts is temperate; the region receives an average of 50 cm of precipitation a year, an unknown but presumably small portion of which enters the bedrock flow system. The bedrock surface is an unconformity with the glacial surficial system which overlies it. A weathered zone of variable thickness occurs at the surface of the bedrock unit and most likely averages one meter thickness. It is not known where recharge enters the system, though it is likely that it occurs at the weathered bedrock surface.

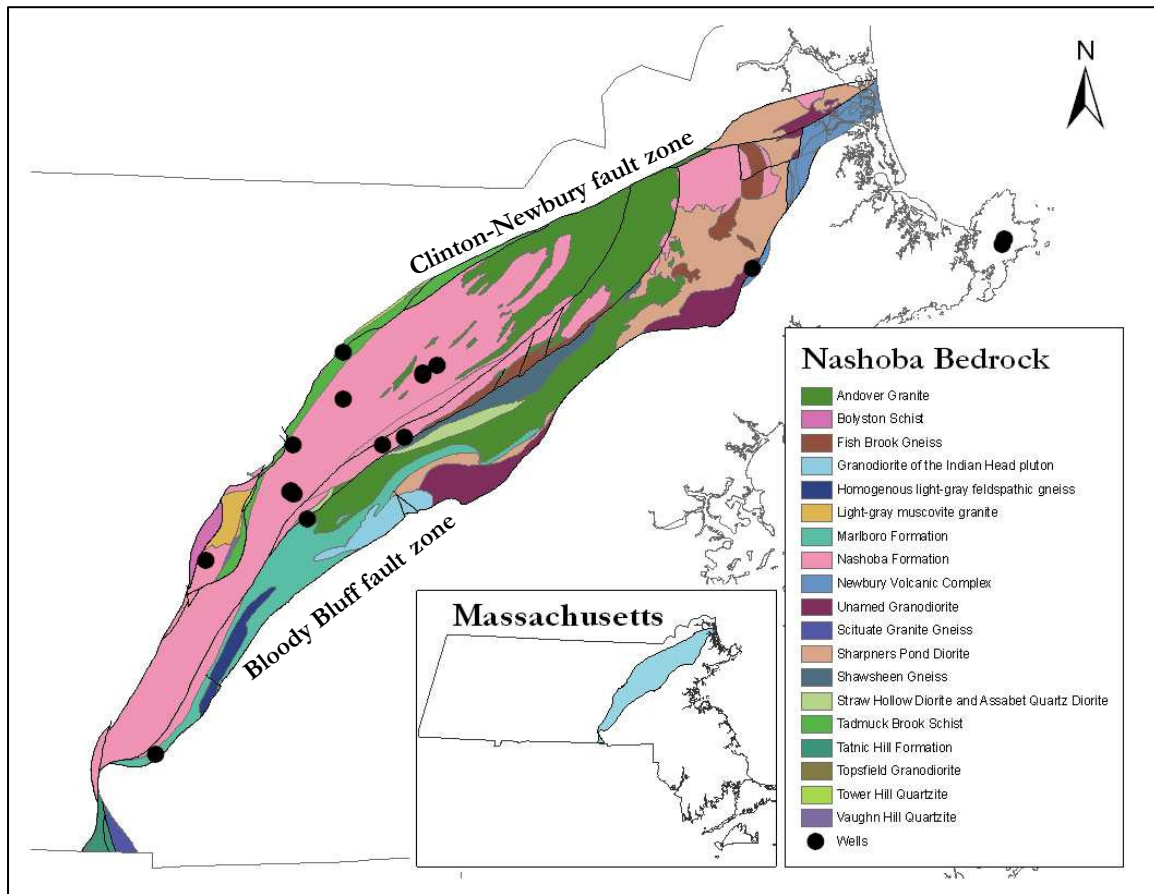


Figure 103. Bedrock Geological Map of the Nashoba terrane in eastern Massachusetts, U.S.A. Wells logged in this study are marked by black dots.

2.4 Results and Discussion

A total of 3,108 meters of borehole were logged with an average well depth of 179 meters. The deepest well was 330 meters deep while the shallowest was 33 meters. Wells studied were in three rock types; five wells were in amphibolite, nine wells were in schist and the remaining three wells were in granitic rocks. All of the wells were cased into bedrock to avoid flow from the overlying surficial system. The glacial materials which overlie the bedrock are variable in thickness and content; for the most part they are approximately five meters thick, nonsorted, unstratified sands with some clay, silt and boulders.

2.4.1 Fractures

A total of 1,905 fractures were identified and measured in the seventeen wells studied in the Nashoba Terrane an average fracture frequency of 0.64 fractures per meter. Three fracture types were identified in the Nashoba Terrane: foliation parallel fractures (FPF), subhorizontal unloading joints and tectonic joints. The foliation direction in the Nashoba terrane is northeast and all fractures that are parallel to this trend are FPF. The direction of strike is approximately 40° with an average dip of $70^\circ \pm 10^\circ$ (Figure 2). FPF comprise 40% of the total fractures in the terrane. Subhorizontal unloading joints are fractures which have a dip less than 25 degrees; these joints comprise 10% of the total fractures identified in the terrane. The final fracture type is tectonic joints, which have variable orientation and comprise 50% of the total fractures identified in this study.

It has been proposed that the initial propagation of fractures is related to the *in situ* stresses at work during that propagation (Barton, 1995 and 1997; Morin and Savage 2004 and 2005). In other words, the orientation of the stress plays a role in determining the orientation of a fracture. It is therefore likely that orientation trends noted in the fracture data are related to the tectonic history of the terrane. For example, the current stress direction in the eastern United States is approximately east-northeast and compressional (World Stress Map). Two tectonic joint groups identified in this study, oriented east-west and north-south, are likely related to this regional compressional stress. Additionally, while the origin of the subhorizontal unloading joints is a subject of much debate; the most likely source is unloading from isostatic rebound following glaciation or unroofing (Wise, 2005).

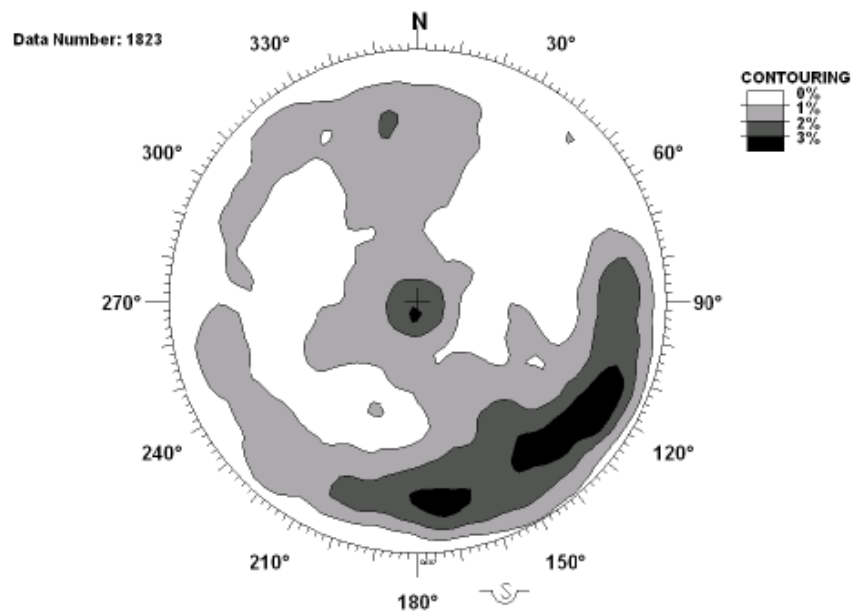


Figure 104. Stereonet of all fractures measured in the Nashoba terrane with a 1% contouring interval.

2.4.2 Depth Dependence

The frequency of fractures in the Nashoba terrane decreases with depth below ground surface. Figure 3 is cumulative frequency graph of the Nashoba wells. Each well is represented by a line, and the slope of each line represents the change in fracture frequency; the steeper the slope the faster the decline in frequency. The variability of these results is high. By 150 meters below ground surface the fracture frequency varies by over 275 fractures; however, the frequency decreases in every well. The fracture frequency of all data is 0.64 fractures per meter (fracts/m); however this value decreases significantly with depth. Table 1 contains the change in fracture frequency between the upper thirty meters of each well and the lowest thirty meters; a positive value denotes an increase in fracture frequency while a negative value denotes a decrease in frequency. In all cases there is a decrease, or negative change with depth. The average fracture frequency in the upper thirty meters of shallow bedrock is 0.76 fracts/m while the average frequency at 270 meters below ground surface is only 0.33 fracts/m (Table 2). Similarly, the median in the upper thirty meters is 0.70 fracts/m while the median at 270 meters below ground surface is 0.33 fracts/m (Table 2).

Figure 4a is a histogram of all fractures identified in the Nashoba terrane broken down into fracture type. The frequency of FPF and tectonic joints decreases significantly with depth in the Nashoba terrane. In schist, the frequency of FPF in the upper 30 meters is between 0.3 and 0.4 fractures per meter; FPF in amphibolite units is the same. In both schist and amphibolite rocks, the frequency of fractures decreases to approximately 0.10 fractures per meter below 100 meters and is 0.05 fractures per meter at 200 meters below ground surface. This trend is not seen in subhorizontal joints. The frequency of these fractures is approximately 0.1 fractures per meter, in all three rock types, near the surface and at 100 and 200 meters below the ground surface. The frequency of tectonic joints in schist is approximately 0.5 fractures per meter in the upper 30 meters and decreases to 0.3 fractures per meter below 100 meters. In amphibolite, the frequency is approximately 0.2 fractures per meter in the upper 30 meters and decreases to approximately 0.15 fractures per meter below 100 meters.

Snow (1969) proposed that a decrease in permeability with depth was due to decreased abundance and aperture of fractures with depth. Additionally, laboratory studies showed that the permeability of a single fracture was sensitive to applied stresses, such as *in situ* or tectonic stresses (Gangi, 1978; Brace, 1978; Sayer, 1990). The decrease in fracture frequency seen in the Nashoba wells is likely reflected throughout the terrane. It is likely then, that this decrease in fracture frequency is the result of *in situ* stress in the subsurface. Further, the dense igneous and metamorphic rocks of the Nashoba terrane have virtually no primary porosity so decreased fracture abundance and aperture likely lowers the permeability of the rock unit with depth.

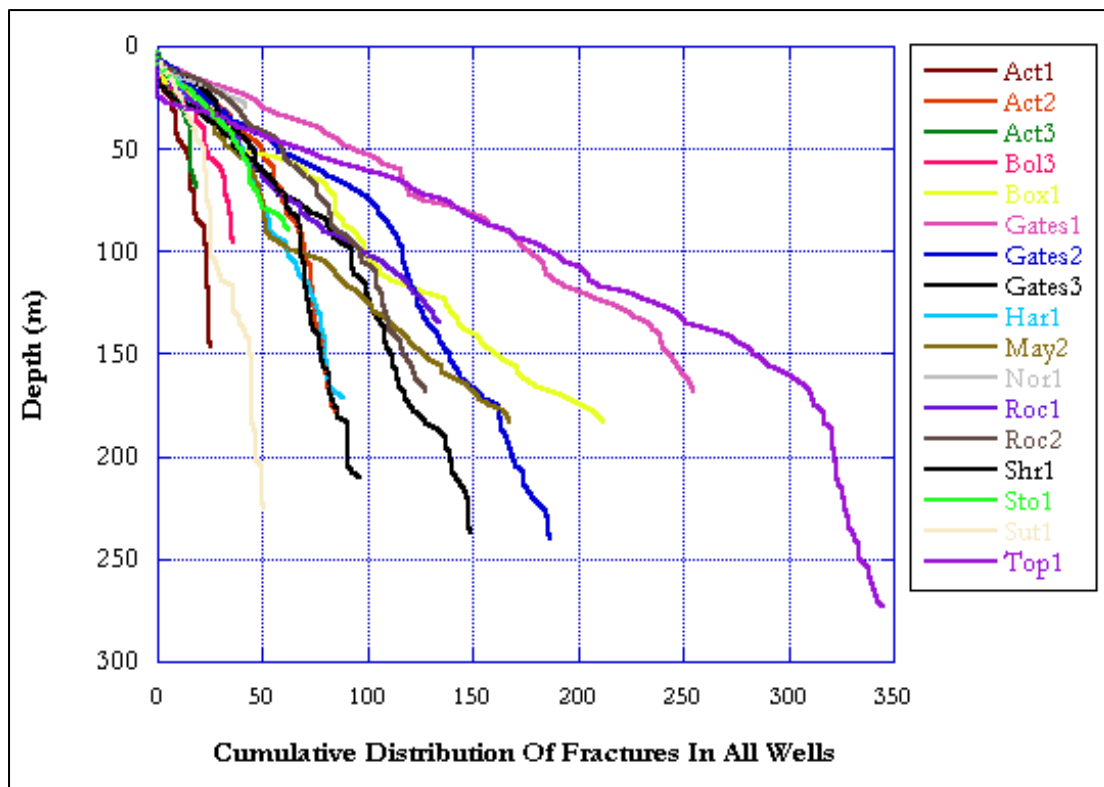


Figure 105. Plot of the cumulative fracture distribution versus depth in the Nashoba terrane. Each well is represented by a line.

Table 5. Variability of fracture frequency by depth in the Nashoba wells.

Well I.D.	Fracture Density (fracts/m) change with Depth	Total depth of Well (m)
Nor1	n/a	33
Act3	-0.30	67
Sto1	-0.01	92
Bol3	-0.57	97
Roc1	-0.62	136
Act1	-0.27	152
Roc2	-1.21	168
Har1	-0.40	171
Gates1	-1.30	179
Act2	-0.53	181
Box1	-0.70	183
May2	-0.77	183
Shr1	-0.27	214
Sut1	-2.70	232
Gates2	-0.53	242
Gates3	-0.70	244
Top1	-2.70	366

Table 6. The average fracture frequency and the median fracture frequency in the Nashoba wells with depth.

Depth (m)	Average Fracture Frequency (fracts/m)	Median Fracture Frequency (fracts/m)
30	0.76	0.70
60	0.84	0.67
90	0.62	0.29
120	0.57	0.36
150	0.57	0.23
180	0.54	0.35
210	0.23	0.20
240	0.24	0.27
270	0.33	0.33
300	0.10	0.10

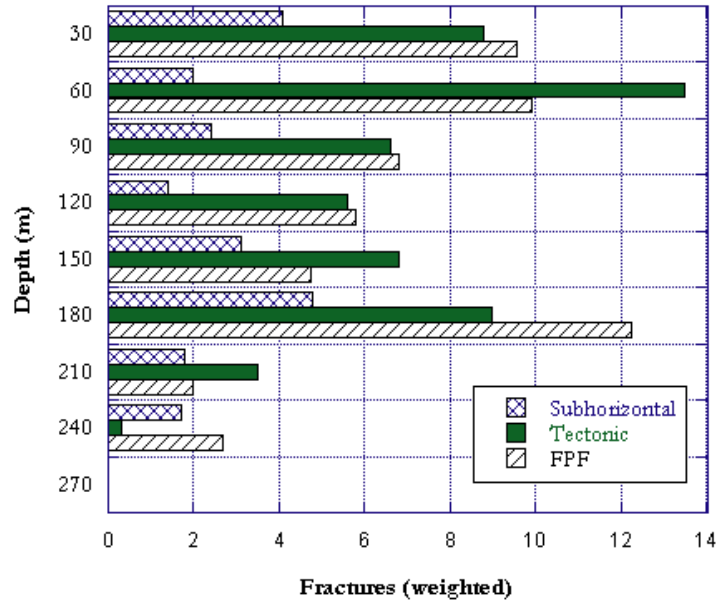


Figure 106a. Histogram of all fractures versus depth broken down by the three fracture types. Each 30 meter bin is divided by the number of wells which reach that bin depth in order to weight the histogram to account for variable well depth.

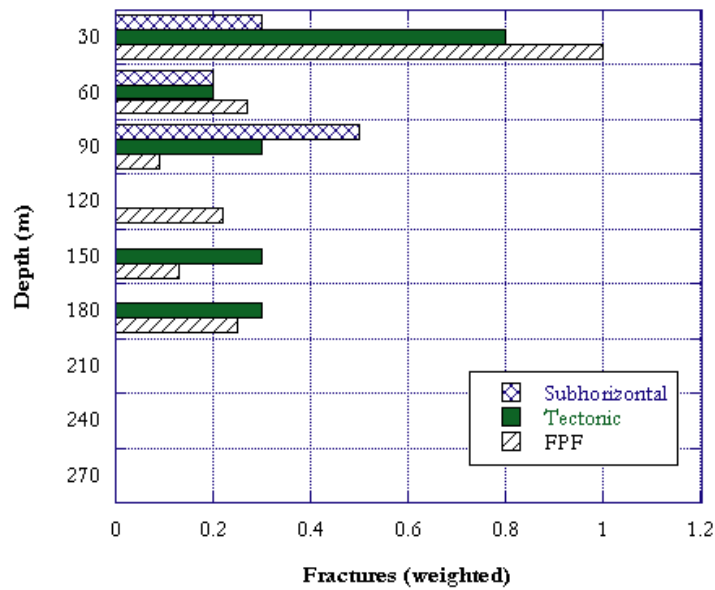


Figure 106b. Histogram of flowing fractures, versus depth broken down by the three fracture types. Each 30 meter bin is divided by the number of wells which reach that bin depth in order to weight the histogram to account for variable well depth.

2.4.3 Fracture Flow

Flowing fractures were determined using the heat pulse flowmeter. Of the total fractures identified in this study only four percent were found to be flowing. Of the flowing fractures 32 percent are FPF, 17 percent are subhorizontal and the remaining 51 percent are tectonic joints (Figure 4b). There are several dominant fracture orientation sets identified in all the wells which reflect orientation distributions discussed above. The orientation sets include: subhorizontal unloading joints; northeast trending FPF; as well as east-west trending, north-south trending and northwest trending tectonic joints. Results of this study suggest that the orientation of a fracture does not determine whether it flows; however, there are a significant number of subhorizontal unloading joints contributing to flow. This finding implies that shallow dipping features may play an important role in the transmission of fluids in the Nashoba terrane.

The frequency of flowing fractures also decreases with depth in the Nashoba terrane. Additionally, no flow was noted below 170 meters depth (Figure 4b). Fractures are less likely to have apertures large enough to transmit groundwater with depth in bedrock environments (Snow, 1969; Legrand, 1954 and 1967; Davis and Turk, 1964). It is likely, based on these results that the *in situ* stress in the subsurface is acting to decrease the aperture of fractures. The reduction of fracture aperture, as well as the abundance of fractures, likely acts to limit the flow of groundwater with depth.

Most of the flow in the wells studied in the Nashoba terrane is constrained to the upper 100 meters of shallow crust (Figure 5a and b). Similar values been proposed before (Legrand, 1954 and 1967; Davis and Turk, 1964). Figures 5a and 5b show that the number of flowing fractures, as well as the magnitude of flow from those fractures, decreases significantly below 100 meters. The smaller number of flowing fractures below 100 meters is likely also the result of a decrease connectivity due to the significantly lower frequency of fractures below that depth. The significantly lower magnitude of flow from fractures below 100 meters is likely due to *in situ* stress at that depth reducing the permeability of individual fractures significantly. Additionally, there are no flowing subhorizontal fractures below 100 meters depth, which is further evidence that shallow dipping fractures play an important role in the transmission of fluids (Figure 5b).

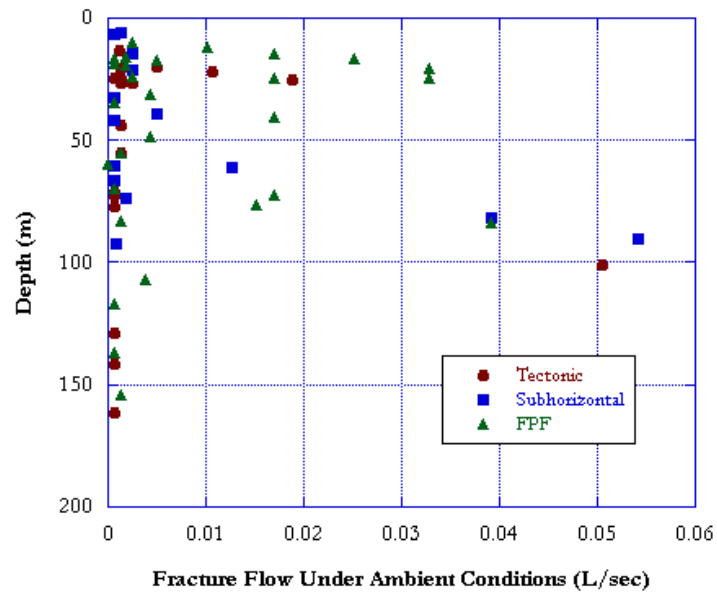


Figure 107a. Scatter plot of the magnitude of flowing fractures under ambient conditions. Points are broken down by fracture type.

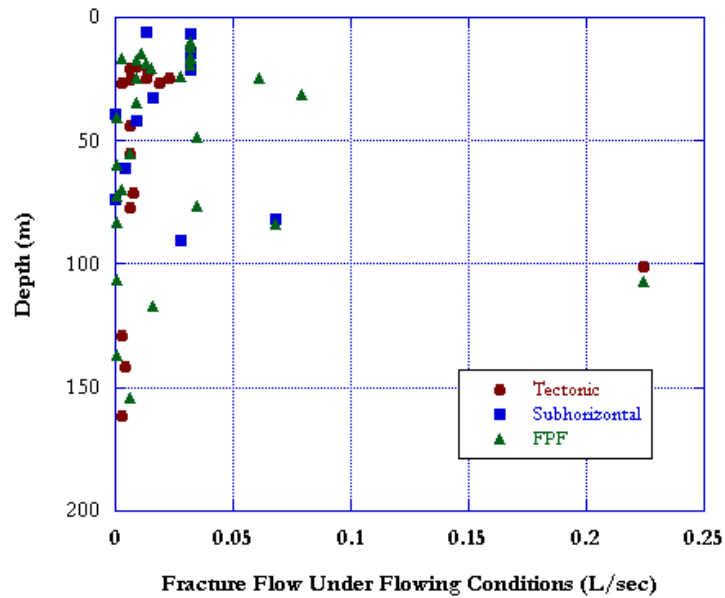


Figure 107b. Scatter plot of the magnitude of flowing fractures under pumping conditions. Points are broken down by fracture type.

2.4.4 Temperature

Figure 6 is a temperature versus depth profile wells logged for this project. In the subsurface, the temperature of groundwater increases with depth. A plot of these temperature profiles can yield important information about the flow system, like the depth of flowing fractures in the borehole. In this study, the temperature at top of the wells is higher than expected for a fractured crystalline bedrock system due to exposure to the surface; however in each profile the temperature reaches its “natural” level, of approximately 11 degrees Celsius, between thirty and fifty meters. Sudden shifts in temperature are most likely related to fracture flow into the borehole (Drury et al., 1984; Drury, 1989; Barton et. al, 1995 and 1996). Between fifty and one hundred meters the gradient of each profile varies a great deal and the gradient is often unstable. The variability of the temperature gradients in this fifty meter zone is related to the influence of groundwater entering the borehole through connected fractures. Below 100 meters, gradient of all the wells stabilizes significantly which suggests that there is little to no contribution of groundwater from fractures below that depth. The gradient in the wells ranges from 23 degrees Celsius per km to 12 degrees Celsius per km. This temperature plot confirms the fracture and heat pulse flow meter results discussed above. The temperature profiles suggest that there is no significant fracture flow entering the wells below 100 meters depth.

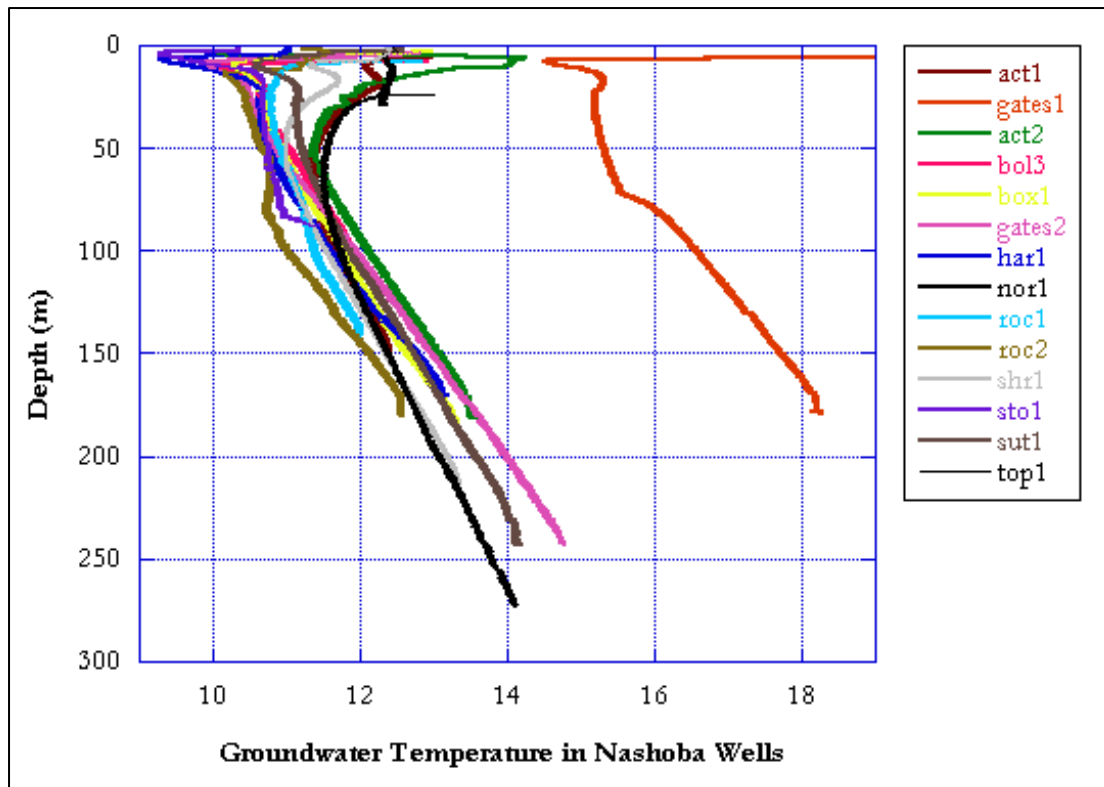


Figure 108. Temperature vs. Depth profiles for all wells in the Nashoba terrane.

2.5 Summary and Conclusions

The Nashoba is a bedrock terrane located in Eastern Massachusetts, U.S.A. The Nashoba, which is primarily composed of metasedimentary and metavolcanic rock units, is highly fractured. Fractures are the result of subsurface stresses from geologic events such as tectonics and glaciation. Borehole geophysics was used on seventeen previously drilled bedrock wells throughout the Nashoba terrane to characterize fractures and fracture flow in the terrane. Fractures were found to exist in fracture sets which are repeated throughout the terrane. These sets are: foliation parallel fractures that are northeast trending, subhorizontal unloading joints that dip less than 25 degrees, and tectonic joints of variable orientation.

The frequency of fractures measured in the subsurface is 0.64 fractures per meter; however, the abundance of fractures decreased with depth across the terrane. The decrease in frequency varied by well. Foliation parallel fractures and tectonic joints were found to decrease significantly with depth across the terrane while the frequency of the subhorizontal unloading joints was not found to decrease.

Heat pulse flowmeter results revealed that approximately 4% of fractures were contributing to flow in the studied wells. Flow below 100 meters was minimal and no flow was noted below 170 meters. These results suggest that the abundance of flowing fractures as well as the aperture of fractures decreases with depth. This decrease in fracture abundance and aperture likely contributes to decreasing permeability with depth in the Nashoba terrane. Heat pulse flowmeter results and borehole temperature profiles suggest that flow in the Nashoba terrane is largely constrained to the upper 100 meters of shallow bedrock. These results have significant implications for future development of the Nashoba as a drinking water resource. Sustainable groundwater is most likely to be found in the upper 100 meters of shallow bedrock. The likelihood of finding a sustainable groundwater source below this depth is minimal and attempts to develop this resource could be costly. The minimal possibility of high groundwater yield versus the cost of drilling should be weighed before attempts to develop this resource are undertaken.

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